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DETECTION AND IDENTIFICATION CONTRAST SENSITIVITY IN RESPONSE T--ETC(U)

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Five well-practiced observers set detection and identification contrast thresholds for Snellen-letter stimuli of different sizes (i.e., fundamental spatial frequencies) under the following conditions: moving (three velocities) vs. stationary, six rotations in the picture plane, and flickering (five temporal frequencies). The subjects' contrast sensitivities for Snellen-letter stimuli were also compared to their contrast sensitivity functions (CSFs) for both static and moving sinusoidal gratings. In a final experiment, subjects adapted to stationary spatial-frequency gratings and set contrast thresholds for letter stimuli

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Major results included the following:

1. For stimuli rotated 0° to 15°, there were almost constant differences on log-log axes between detection and identification sensitivities, suggesting that observers may have used for identification spatial frequencies less than 1.5 times those used for detection.
2. Beyond 30° rotation, decline in sensitivity beyond the peak spatial frequency is more rapid for identification than for detection.
3. Data suggest that the ratio of spatial frequencies used for the indentification vs. the detection of letters changed from something less than 1.5 at 0° to 1.5-2.5 at 75°.
4. Together, variations in the size and rotation of Snellen-letter stimuli accounted for a decline in detection sensitivity of roughly two-thirds; in identification sensitivity, of almost three-fourths.
5. For frequencies below 20 Hz, temporal frequency (or velocity) had little effect on detection and identification contrast sensitivity for Snellen-letter stimuli with a fundamental spatial frequency of 2.28 cycles/degree. Beyond 20 Hz, both detection and identification sensitivities declined with increases in temporal frequency.
6. With different temporal frequencies, the ratio of detection contrast to identification contrast was roughly constant (about .73) up to a cutoff of 20 Hz. Beyond 20 Hz, the ratio declined gradually to a low of .39.
7. A decline in identification contrast sensitivity with increasing spatial frequency was dependent upon the velocity of the moving Snellen-letter target, with higher velocities resulting in greater declines.
8. With stimulus motion, contrast sensitivities to Snellen letters lost the low spatial-frequency falloffs apparent in the curves for stationary letters.
9. Detection-to-identification threshold contrast bandwidths rose from 1.1 for stationary stimuli to 2.88 for stimuli drifting at 16.61 degrees/second.
10. Slow movement of Snellen-letter stimuli tended to enhance detection sensitivity relative to stationary conditions; fast movement enhanced detection sensitivity only at lower spatial frequencies and depressed it somewhat at the higher spatial frequencies. Fast movement also depressed identification sensitivity.
11. At low spatial frequencies, 5-Hz flicker yielded the highest contrast sensitivities; at intermediate frequencies, 1-Hz flicker. At the highest spatial frequency, 1-Hz and 5-Hz flickering yielded comparable sensitivities.
12. By calculation, the optimum temporal frequency used for the identification of flickering Snellen-letter stimuli having a fundamental spatial frequency of 1.43 cycles/degree was 1.72 times the optimum temporal frequency used for detection. The corresponding figure for stimuli with a fundamental spatial frequency of 3.81 cycles/degree was 1.60; for 7.61 cycles/degree, 1.07. At and beyond 8.56 cycles/degree, detection and identification should be optimal at the same temporal frequency.
13. One observer was found to have significant losses of contrast sensitivity to stationary sine-wave gratings. This deficiency was also manifest in his contrast sensitivities to Snellen-letter stimuli. However, his contrast sensitivities were nearly normal in response to moving gratings and letters.

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October 1981

# DETECTION AND IDENTIFICATION CONTRAST SENSITIVITY IN RESPONSE TO COMPLEX STATIONARY AND MOVING TARGETS

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CAPT GIRARDEAU, MO 63701

Dr. Petersik

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## PREFACE

The work discussed in this report was performed for the U.S. Air Force by Southeast Missouri State University (Cape Girardeau, Missouri) under the terms of contract No. AFOSR-81-0088. The work was performed during the period 01 February 1981 through 30 September 1981. Significant portions of the writing of this report were completed by the author at Ripon College (Ripon, Wisconsin).

The contract monitor for this effort was Dr. G. M. Haddad, Bolling Air Force Base, D.C. 20332.

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# I. INTRODUCTION

## A. Background

The notion that the visual system processes visual information by conducting something like a Fourier analysis or spatial-frequency analysis has been gaining widespread acceptance over the last ten to twenty years (for reviews see Braddick, et al., 1978; Sekuler, 1974; Graham, 1981). The strength of this approach derives from Fourier's theorem, which demonstrates that any mathematical function can be described in terms of the sum of a number of sinusoidal functions. Since a visual scene is nothing more than a function relating luminance to spatial position (disregarding wavelength), it follows that any visual stimulus can also be described by a set of sinusoids. In this case, the relevant sinusoids are sine-wave gratings, or luminance distributions whose profiles are sinusoidal. Such gratings are usually specified by at least four parameters: spatial frequency, or the rate of change of luminance over space (in cycles per degree of visual angle, or cycles/degree), contrast (defined at $L_{max} - L_{min}/L_{max} + L_{min}$, where $L_{max}$ and $L_{min}$ are the maximum and minimum luminances of the grating, respectively), phase (the location of peaks and troughs of the distribution relative to some fixed locus), and orientation.

Recent studies using such stimuli (Campbell & Robson, 1968, Schade, 1956) suggest that the human visual system behaves like a bandpass filter with respect to spatial frequency. Furthermore, studies suggest that the visual system

is linear to a first approximation, both at threshold contrasts (Campbell & Robson, 1968) and at suprathreshold contrasts (Ginsburg, Cannon, & Nelson, 1980). These findings render the human visual system open to linear-systems types of analyses, a fact which Ginsburg (1978) has taken advantage of in his model of information processing within the human visual system.

Still other studies have examined the human contrast sensitivity function (CSF) in more detail (Blakemore & Campbell, 1969; Pantle & Sekuler, 1968). CSF relates the reciprocal of threshold contrast (sensitivity) to spatial frequency, and for most normal observers is an inverted U-shaped function with a peak near 3-5 cycles/degree. Adaptation of the visual system to individual spatial frequencies (Blakemore & Campbell, 1969; Pantle & Sekuler, 1968) results in a localized depression of the CSF, centered at the adapting frequency and about 1.5 octaves in width. These results have been interpreted to mean that the normal CSF is an envelope of the CSFs of several narrower spatial frequency channels, each of which can be thought of as a bandpass filter admitting a limited range of spatial frequencies.

Ginsburg (1978) has argued that, under certain conditions, the visual system can be considered as passing spatial information through roughly seven distinct channels or filters, each of which is tuned differently with respect to spatial frequency. The evidence for Ginsburg's proposal includes many demonstrations, one of which warrants detailed discussion: A portrait of a human face was passed through eight distinct filters

whose center spatial frequencies were one octave apart and whose bandwidths were two octaves. Each successive filtered portrait revealed information useful to a successively more refined perceptual task -- the lowest filtered portrait passed only gradual contrast changes, so that it was apparent some figure was present; the next, an elliptical shape; next generalized facial information; information regarding age, sex, etc.; information required for identification of the face; details of hair, eyes, etc.; and so on.

In an example that is especially relevant to the present research, Ginsburg (1978) compared the CSF to the more traditional method of assessing visual performance (i.e., Snellen acuity) in an effort to elucidate the filter concept. He began by determining the number of spatial frequencies required for identification of two common Snellen letters, E and L. This was done by filtering each of the letters with successively broader low-frequency bandpass filters and showing that about 2.5 cycles per object (a relative measure that does not depend upon viewing distance as does cycles/degree) are required for identification of the L. It was suggested that a spatial filter with a bandwith of 1.5-2.5 cycles per object (or an average of 2.0 cycles per object) is required for Snellen letter recognition in general. This means that, given a Snellen letter of any size (i.e., of any fundamental spatial frequency), the spatial information required for identification of the letter will be contained in a range of spatial frequencies about 1.5 to 2.5 times the fundamental spatial frequency. Ginsburg also arrived at this same figure

(1.5 to 2.5) by a different method of estimation, one that is described in a later section of this report. Furthermore, after obtaining the CSFs of several individuals, Ginsburg was able to predict Snellen acuity on the basis of the above analysis. (However, Snellen acuity cannot be used similarly to predicate an observer's CSF, except over a restricted range).

Although Ginsburg's determination of the spatial bandwidth required to recognize Snellen letters and his subsequent prediction of Snellen acuity based upon CSF represents a major advance in visual science, it is incomplete inasmuch as the stimuli he used were stationary and were always perpendicular to the observer's line of sight. Since most of the visual world is glimpsed under conditions of movement (either of the observer or of the observed object) and since not all objects face the observer directly, the present experiments were undertaken partially as a means of extending Ginsburg's analysis to such conditions.

The pioneering psychophysical studies of Kulikowski and Tolhurst (1973) and of Tolhurst (1973) have shown that with moving sine-wave gratings, most combinations of spatial frequency and velocity give rise to two perceptual thresholds. One of these is a "movement" or "flicker" threshold, and the other is a "pattern" threshold. It has been postulated that the visual system actually consists of two broad classes of channels and that each class has its own spatio-temporal response properties (see Breitmeyer & Ganz, 1976 and Petersik, 1978 for a review of these properties). The so-called

"transient" channel responds best to moving or flickering stimuli of relatively low spatial frequency and provides little information about the detailed structure (i.e., high spatial-frequency information) of the stimulus. On the other hand, the "sustained" channel prefers relatively stationary or slowly moving stimuli of relatively high spatial frequency and does provide information about detail (but not movement). This distinction has recently found support in the physiological literature (e.g., Sekuler, Pantle, & Levinson, 1978). Presumably, the Snellen-letter recognition studies of Ginsburg cited above make use almost solely of the sustained system. Depending upon their contrast, moving targets may be analyzed only by transient mechanisms (which would provide little information important to discrimination or recognition) or by both transient and sustained mechanisms. Thus, there is good reason to replicate the studies of Ginsburg under conditions in which both gratings and targets move.

Projective geometry shows that the two-dimensional image on the picture plane (in this case, the retinal image) changes both in shape and size as the object giving rise to the image is rotated about the vertical axis (Petersik, 1978). The geometric analysis suggests that as an object rotates relative to the observer, its spatial frequency spectrum on the picture plane must also change (at least in one dimension). How this change in the spectrum of an object affects target acquisition and recognition is not known. However, the question is of practical importance, since, for example, most of the stimuli approaching a pilot will not be perpendicular to his or her

line of sight. The type of analysis previously employed by Ginsburg should determine how rotation affects visual performance.

Petersik (1980) conducted a preliminary study of the effects of image movement and image rotation on observer contrast sensitivity to Snellen-letter stimuli. Two of the most important findings of that study were that 1) with increasing rotation of targets the slope of the line relating contrast sensitivity to target size (i.e., fundamental spatial frequency) increased, indicating that changes in size of similar magnitude have greater effects on visual performance with successively rotated targets, and 2) identification-to-detection threshold ratio bandwidths increased by a factor of 1.2-1.5 with stimulus movement and, for stationary targets, by a factor of 1.1-1.2 with image rotation; these bandwidths give estimates of the range of spatial frequencies above those used for detection that are used for identification. This latter finding has been used as evidence that there is a changeover in the spatial mechanisms used for identification of a moving target (Ginsburg & Petersik, in preparation).

B. Objectives

Because of technical limitations in the range of stimulus velocities and target sizes in the earlier study of Petersik (1980), the present experiments were undertaken in order to extend the range of stimulus parameters under consideration, to test new stimulus conditions (flicker and spatial-frequency adaptation), and to gather more data in each experimental

condition. Specifically, the objectives of the present experiments were to:

1) Provide data which can be used to extend Ginsburg's filtering model of visual processing of cases involving visual stimuli and stimuli rotated with respect to the observer's frontoparallel plane.
2) Collect contrast sensitivity data for both "detection" and "identification" thresholds for both moving and stationary Snellen letters of various sizes (i.e., fundamental spatial frequencies).
3) Collect contrast sensitivity data for both stationary and moving sine-wave gratings over a range of visible spatial frequencies.
4) Collect contrast sensitivity data for both stationary and moving Snellen letters that have been rotated to the observer's frontoparallel plane.
5) Relate detection and identification contrast sensitivities obtained with Snellen-letter stimuli to the basic CSFs obtained with stationary and moving sine-wave gratings.
6) Determine how detection and identification sensitivity to Snellen-letter stimuli change when the stimuli are flickered.
7) Determine whether identification sensitivity for Snellen-letter stimuli changes with adaptation to spatial-frequency gratings.

The Snellen-letter stimuli used in the present studies were B, E, V, and L. The amplitude spectra of these letters are shown in Figures 1 through 4 (courtesy of Mark Cannon, Aerospace Medical Research Laboratories, Wright-Patterson AFB, Ohio). Horizontal spatial frequencies in these figures are depicted in the dimension traveling to the upper left; vertical spatial frequencies, to the upper right. As can be seen in the figures, B contains the most energy, followed by E, V, and L. These figures may be used for reference throughout the remainder of this report.

FIGURES 1-4: Amplitude spectra of the letters B,E,V, and L. Horizontal spatial frequencies are shown in the dimension traveling to the upper left of the page. Vertical spatial frequencies are shown in the dimension traveling to the upper right.

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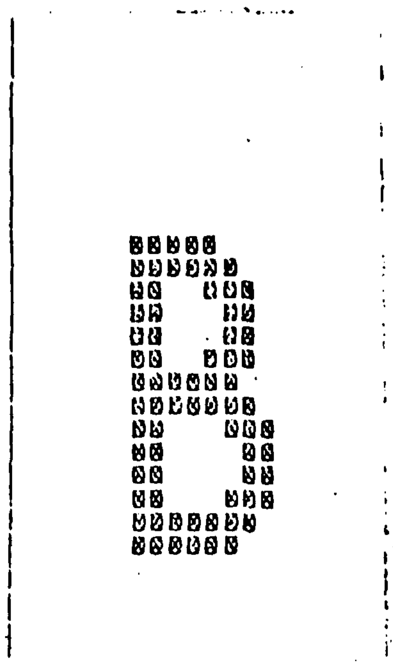

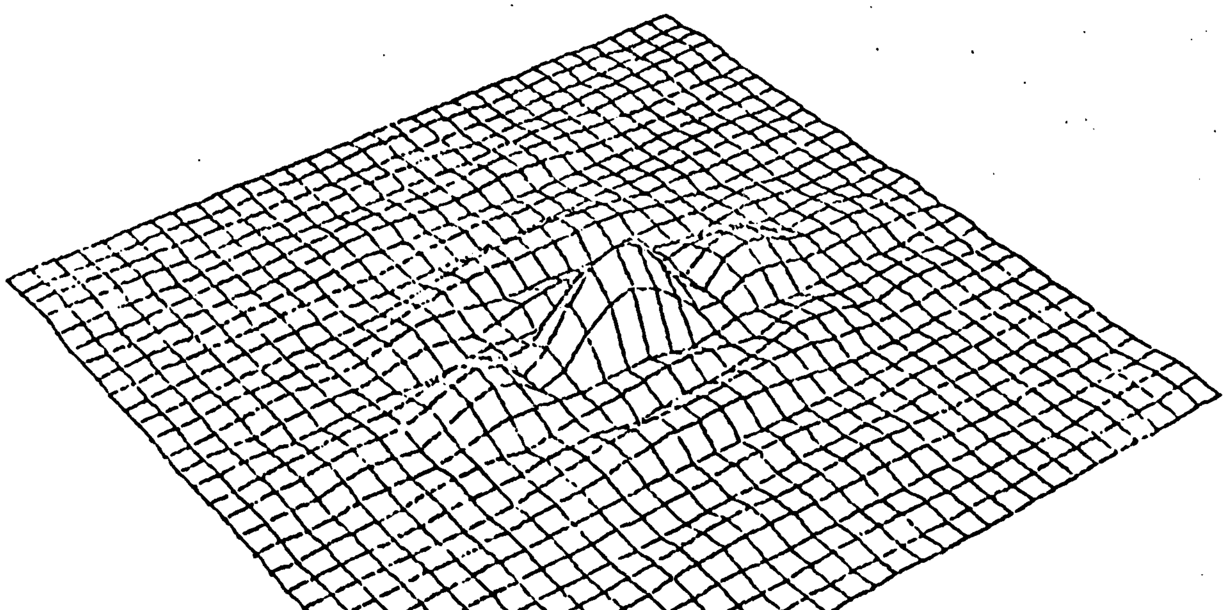

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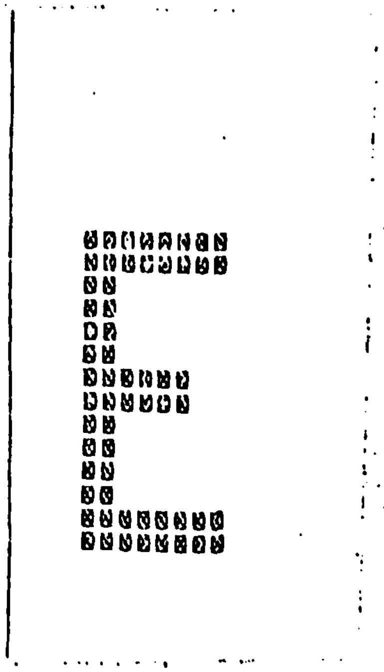

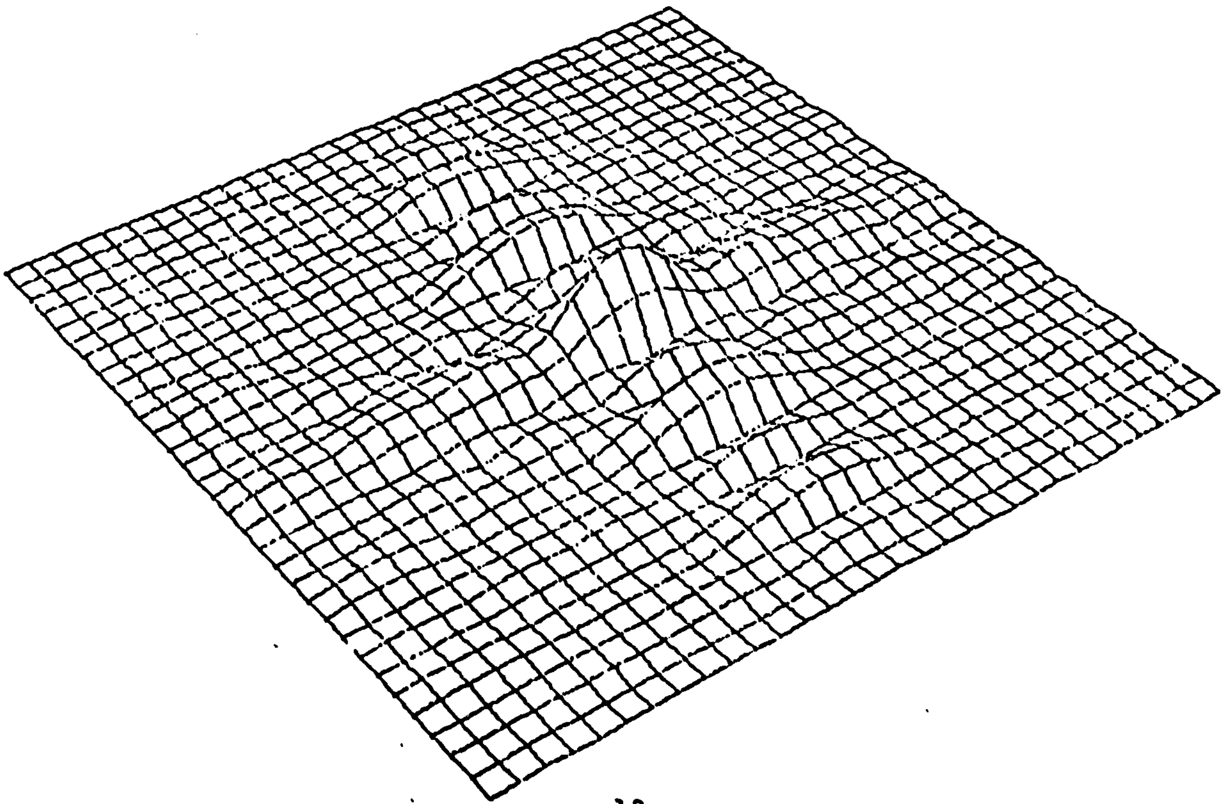

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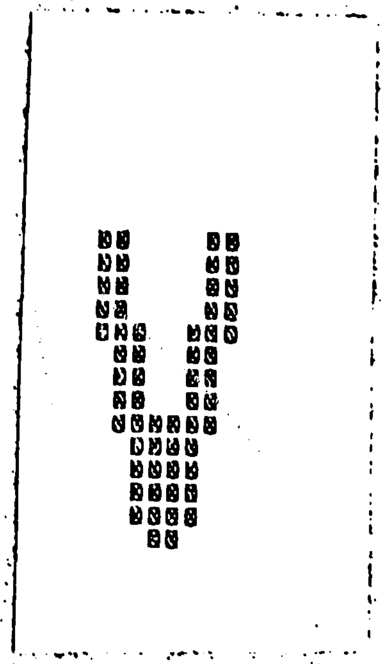

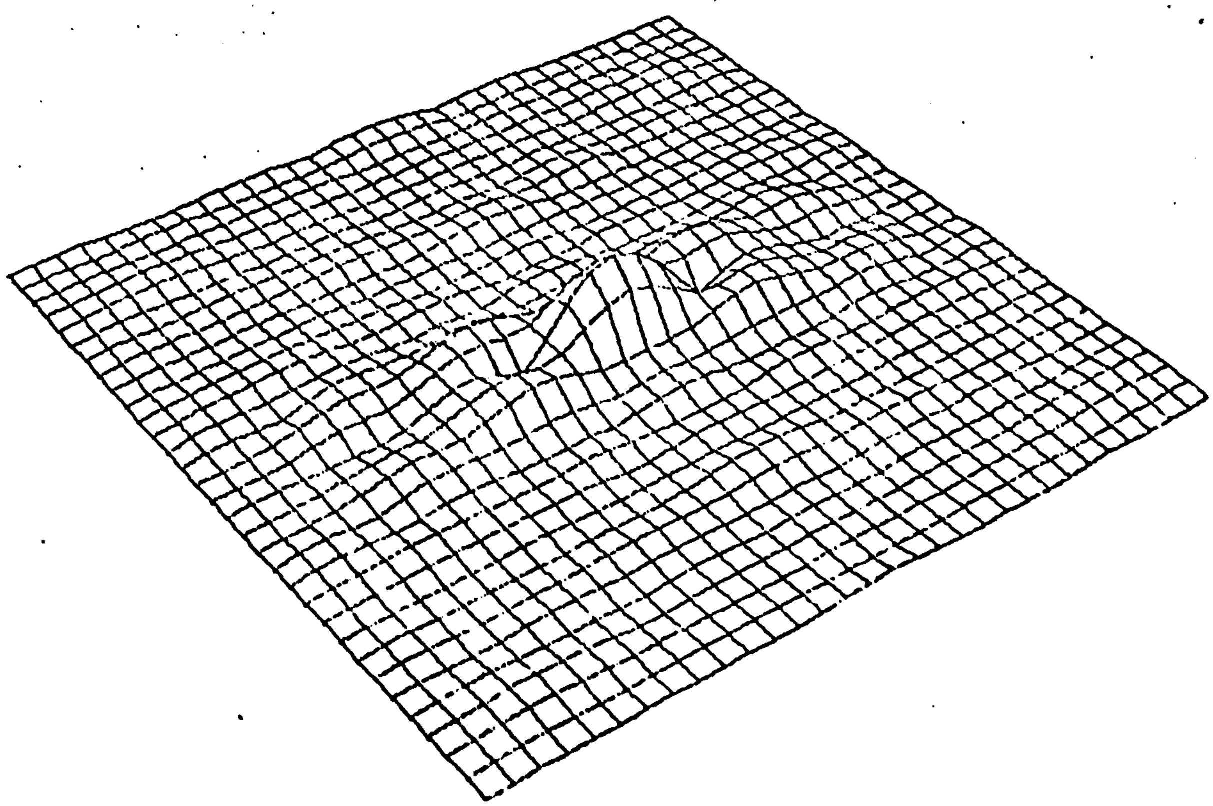

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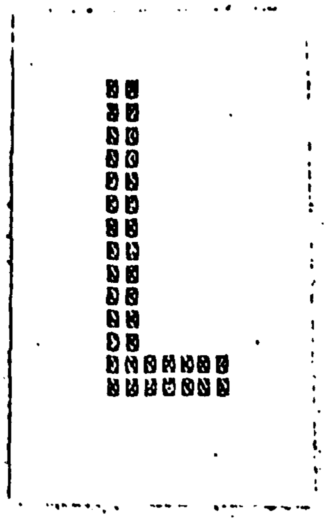
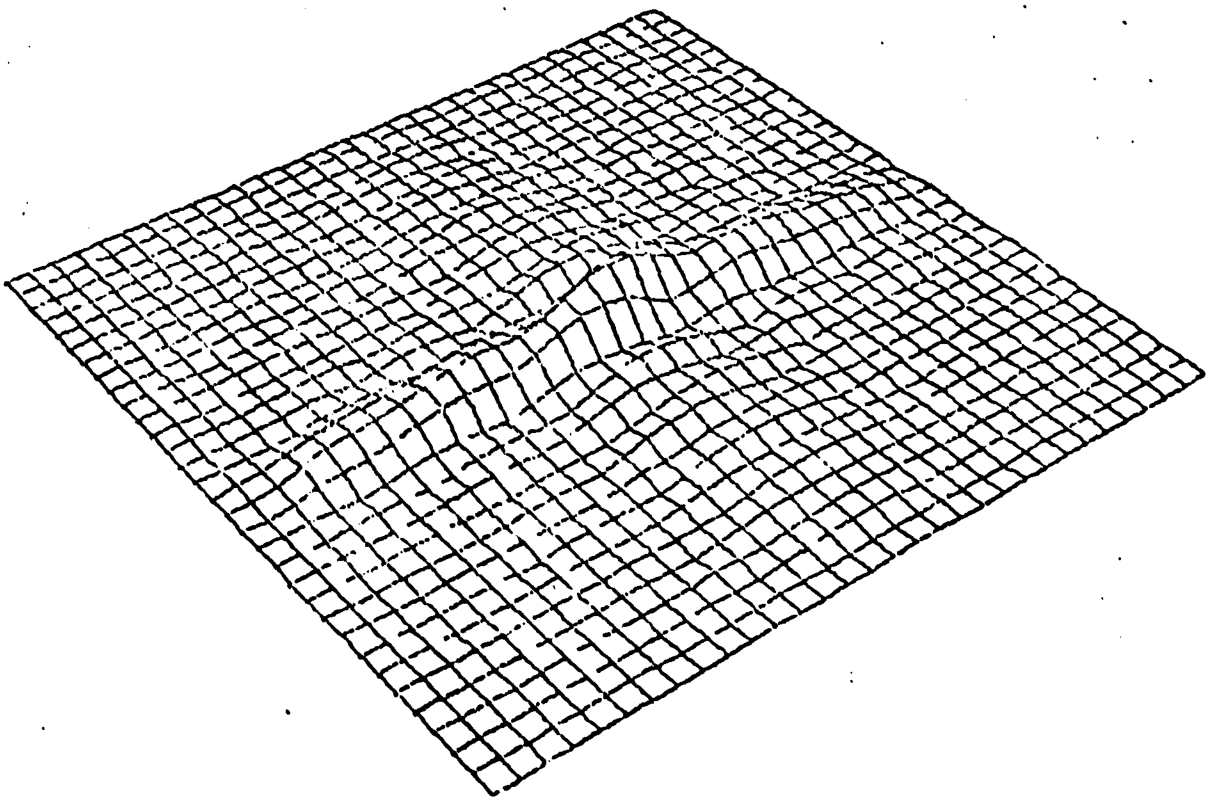




## II. GENERAL METHOD

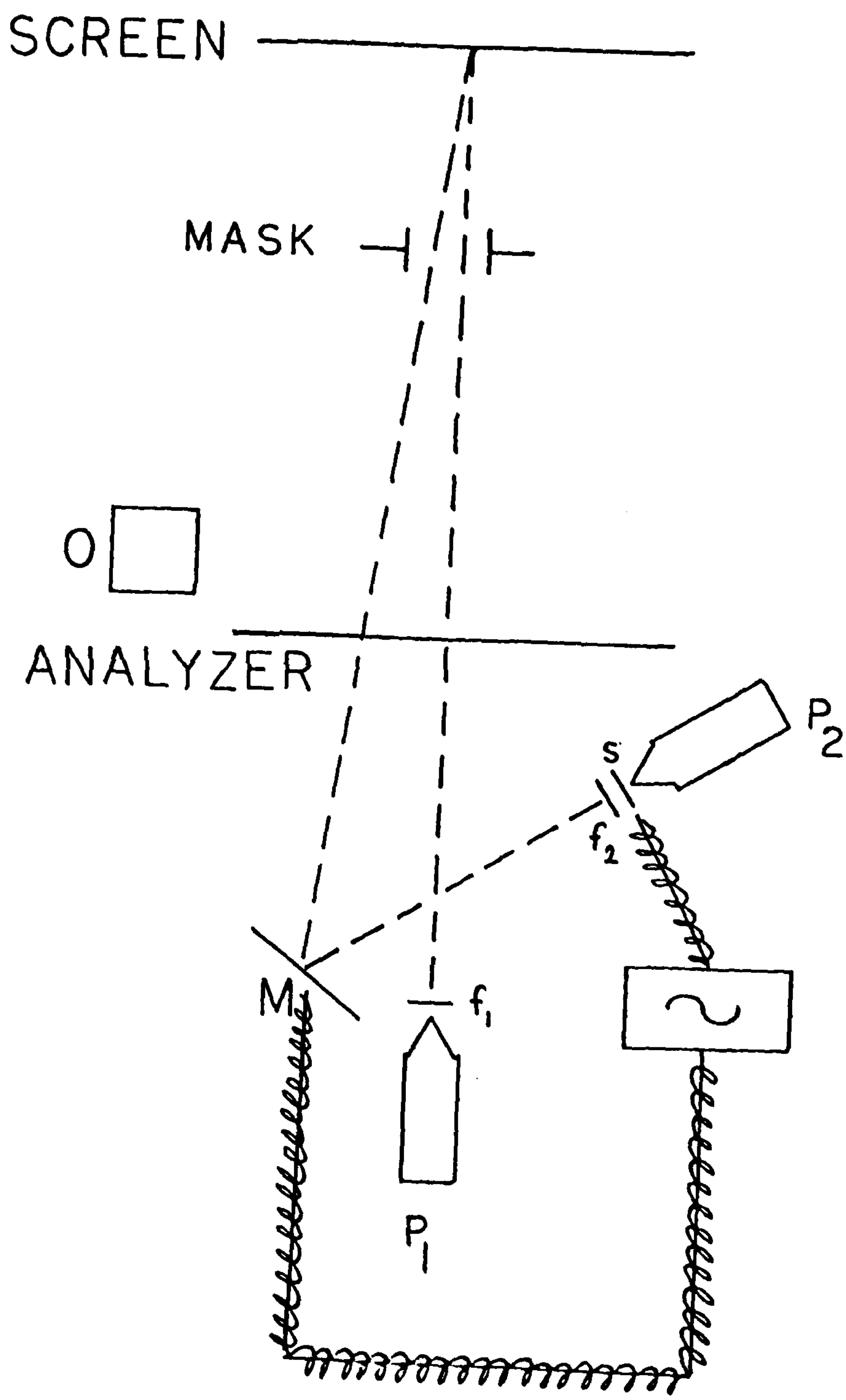
Two distinctly different apparatus systems were used to present stimuli and measure responses in the following series of experiments: To vary the contrast of Snellen-letter stimuli, a cross-polarizing system originally developed at the Aviation Vision Laboratory of the Aerospace Medical Research Laboratories was modified; to generate and vary the contrast of sine-wave gratings, a microcomputer-based system was employed. The following sections describe these systems in detail.

### A. Stimuli and Apparatus - Snellen-letter contrast thresholds

High contrast photographic slides (Kodak 35 mm Kodalith film) of Snellen letters of four different sizes and six different rotations relative to the picture plane were prepared. The particular letters chosen, in order of decreasing energy, were B, E, V, and L. For each of the four sizes, each of these letters was photographed at angles of 0°, 15°, 30°, 45°, 60°, and 75° relative to the camera. The factorial combination of four letters by four sizes by six angles resulted in a total of 96 Snellen-letter stimuli.

The Snellen-letter stimuli were presented through a dual-channel cross-polarizing display system shown schematically in Figure 5. This system has orthogonally oriented polarizing filters ($f_1$ & $f_2$) in front of each of two slide projectors, the stimulus projector ($p_2$) and the luminance projector ($p_1$), which contains no stimulus. The beams from both projectors are passed through a polarizing analyzer, through a

FIGURE 5: Dual-channel cross polarizing system used to present Snellen-letter stimuli in the present experiments. $p_1$: projector 1; $p_2$: projector 2 (stimulus channel); $f_1$: polarizing filter 1; $f_2$: polarizing filter 2 ($f_1$ and $f_2$ are oriented 90° relative to one another); s: shutter; ~: function generator; M: mirror on scanner; O: observer. (See text for details of operation.)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$f_1$
$P_1$

polarizing analyzer, through a mask to restrict the size of the stimulus background, and are superimposed on a screen. Rotation of the analyzer is achieved electromechanically, and is controlled by the observer. Rotation of the analyzer allows the relative contribution of the luminance from each projector to vary while maintaining overall luminance at an approximately fixed level. In practice this allows the observer to manipulate stimulus contrast (cf. Guzman & Steinbach, 1981)

To produce stimulus motion, the $p_1$ beam was reflected from a front-surfaced mirror (M) before passing through the analyzer. The mirror was attached to a scanner that was driven by a waveform generator (Wavetek, model 182A). The waveform generator controlled the frequency and amplitude of the scanner, and therefore also of the mirror and stimulus image. A shutter (s) was placed in front of $p_1$. The shutter was also controlled by the waveform generator so that during one-half of a cycle of mirror rotation the shutter could be closed. Thus, we could arrange to have the stimulus move in one direction only. The closing of the shutter produced a small overall decrease in the luminance level of the display, but at threshold levels of stimulus contrast this change in luminance was barely noticeable (i.e., the luminance contribution of $p_1$ was small).

We tried to produce stimulus movement with both triangular and sinusoidal signals from the waveform generator. Although triangular signals are desirable for producing a

constant-velocity motion, we found that abrupt reversals in the rotation-direction of the mirror resulted in lengthy and considerable "jitter" of the stimulus image. We therefore settled on a sinusoidal signal, but maintained an approximately constant velocity by rotating the mirror through large amplitudes and confining the stimulus movement that passed through the mask to the nearly linear portion of a cycle of a sine-wave signal. A large room partition separated the observer from the apparatus.

Viewing distance, space-average luminance, and screen size varied in some experiments and are reported in later sections. Luminance measurements of stimuli and backgrounds were made for every 0.9° rotation of the analyzer. Contrast was calculated by the formula $L_{max} - L_{min}/L_{max} + L_{min}$, where $L_{max}$ is the luminance of the background and $L_{min}$ is the luminance of the stimulus letter. This system included a digital display whose readout was proportional to the angle of rotation required to reach a threshold could be read directly from the digital display and a corresponding contrast threshold could be later found from a table.

B. Stimuli and Apparatus -- Sine-wave grating thresholds

Sine-wave gratings were generated by a microcomputer-based system originally described by Fritsch and Keck (1978). This system uses a SYM-1 microcomputer (Synertek Systems) interfaced with a display oscilloscope (Hewlett-Packard, model 1340A) coated with a rapid-decay (P31) phosphor. The beam of the CRT is swept horizontally by a ramp signal at the rate of 70 Hz and vertically by a triangle-wave signal

at the rate of 500 KHz. The intensity of the beam is modulated on each vertical sweep by one of 256 values stored in computer memory in the form of a master sine table. For each horizontal sweep, the 256 values in the sine table are read through sequentially twice, producing 512 lines on the CRT screen. In this case, the display produced one-dimensional (i.e., vertically oriented) sine-wave gratings.

On each experimental trial this system allows the experimenter to specify the spatial frequency and velocity (in Hz) of the grating, the direction of movement (if any), and the grating's initial contrast.. The observer can increase or decrease the contrast of the grating by pushing the appropriate button on a remote-control box interfaced with the microcomputer. A digital readout on the microcomputer allows the experimenter to record threshold contrast on each trial.

In the present experiments, viewing distance was held constant at 342.9 cm. At this distance, the screen of the display oscilloscope subtended 1.7° vertically and 2° horizontally. With these conditions, only two cycles of a 1 cycle/degree grating were visible to the observer. Estevéz and Cavonius (1976) recommend that at least three cycles of low frequency gratings be present in threshold experiments in order to avoid spurious low-frequency attenuation. We chose our viewing distance to be roughly comparable to that used in the experiments with Snellen-letter stimuli. In order to guard against low-frequency attenuation, we employed the following measures: 1) as recommended by Estevéz and Cavonius, we surrounded the CRT with cardboard whose color

approximately matched that of the screen and whose luminance was approximately one-half of the screen's space-average luminance; 2) Gratings were viewed with even and moderate ambient illumination in the testing room. As Pantle (1980) has shown, increases in the light adaptation of the observer tend to increase threshold sensitivity to gratings of all frequencies.

In the experiments with sine-wave grating stimuli, the space-average luminance of the CRT was held constant at 20.56 $cd/m^2$.

C. Subjects

Five experienced psychophysical observers served in each of the present experiments except where noted. Three of the observers were undergraduate students, one was a graduate student, and one was the author. Aside from the author, none of the subjects had more than a general understanding of the rationale underlying the present experiments. The four student observers were paid for their participation.

Using the preferred eye (listed below), each of the five observers (MM, MB, MS, RF, and TP) had consistent visual acuity scores of 20/20 when tested with a conventional Snellen chart over the 12 week experimental period. Two observers (MS and TP) required corrective lenses in all stages of the experiments. Subjects were always tested with the eye that yielded the highest visual acuity. Observers using the right eye were MM, TP, and MS; using the left, MB and RF.

Prior to experimental testing, each subject had minimum

of 15 hrs practice setting contrast thresholds with both Snellen-letter and sine-wave grating stimuli. Subjects practiced until they could make a sequence of ten contrast-threshold settings with a standard deviation of no more than ±10% relative to the mean contrast threshold for each of a number of stimuli.

D. Procedure -- Snellen-letter contrast thresholds

All sessions were conducted in a semi-dark room whose only ambient illumination was provided by the apparatus and by hallway lights. To prevent subject fatigue, no subject was run for more than 40 min at a time. On experimental trials, subjects were seated at eye-level in front of a white screen. Subjects were seated a distance of 196 cm from the screen. For the smallest of our stationary letters, two observers (MB and MM) were seated 321.3 cm from the screen. When viewed from 196 cm, the screen subtended 20.7° horizontally and 16° vertically; from 321.3 cm, 12.7° and 9.8°, respectively. The luminance of the background area of the screen was 60 cd/m$^2$ for stationary stimuli and was 20 cd/m$^2$ for moving stimuli.

On each experimental trial the observer fixated an area of the screen midway between vertical black fixation stripes taped to the middle of the top and bottom borders of the screen. On any experimental trial, two of our observers (MB and MM) set either a detection threshold at which contrast the presence of a stimulus could just be perceived or an identification threshold at which contrast the letter

could just be correctly identified. Three of our observers (MS, RF, and TP) first set a detection threshold for a given stimulus, lowered the contrast well below threshold, and proceeded to set the identification threshold for that same stimulus.

Each observer always began a trial at a randomly pre-set level of contrast well below threshold, and increased contrast until threshold was reached. If the observer felt that threshold was inadvertently exceeded on any trial, the trial was re-run. For moving stimuli (with the exception noted below), the observer only viewed the leftward-moving half of a stimulus cycle, the rightward motion being masked by a shutter. Thus, the observer only adjusted contrast during one-half of a motion cycle.

Except where noted below, stimuli were presented on a completely random schedule.

For each type of threshold and every experimental condition, each observer provided 6-8 contrast-threshold estimates.

E. Procedure -- Sine-wave grating contrast thresholds

All sessions were conducted in a semi-dark room whose only ambient illumination was provided by a low-wattage bulb located behind and above the subject so that the CRT screen and cardboard surround were evenly illuminated. Trials were run in 40-50 min blocks. On any trial, the subject fixated a central area of the CRT screen directly above a black fixation stripe located just below the middle of the screen's lower border.

For stationary gratings, subjects set detection-threshold contrasts. For moving stimuli, two subjects (MB and MM) set either detection or identification thresholds in blocks. Subjects MS, RF, and TP again set detection and identification thresholds in succession for each stimulus. The identification threshold in this case was defined as that contrast at which the observer could potentially estimate the number of bars present on the CRT screen.

For stationary gratings, stimuli were presented on a random schedule. For moving gratings, stimuli were presented in randomized blocks: Temporal frequency remained constant over five randomly presented spatial frequencies. Blocks of temporal frequencies were randomly ordered. Movement direction was determined randomly on each trial.

Each observer provided ten threshold estimates for each type of threshold at each combination of spatial and temporal frequency.

# III. EXPERIMENTS WITH STATIONARY STIMULI

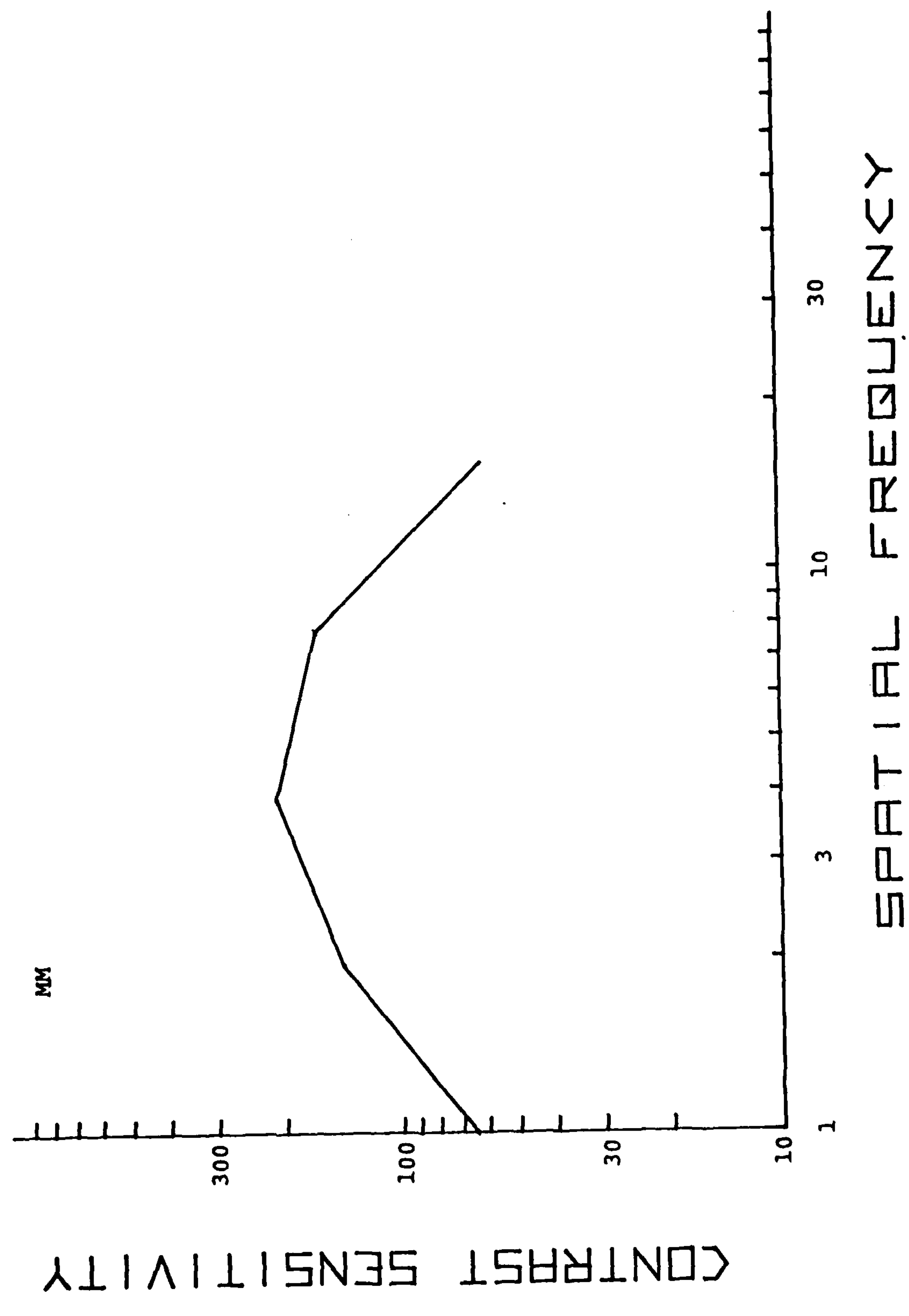
In these experiments observers adjusted both detection and identification contrast thresholds in the presence of stationary stimuli. Observers' heads were unrestrained in order to simulate normal viewing conditions, although the observers were instructed to avoid making head movements as much as possible. Observers were instructed to maintain a steady but comfortable fixation. Viewing was monocular with the preferred eye.

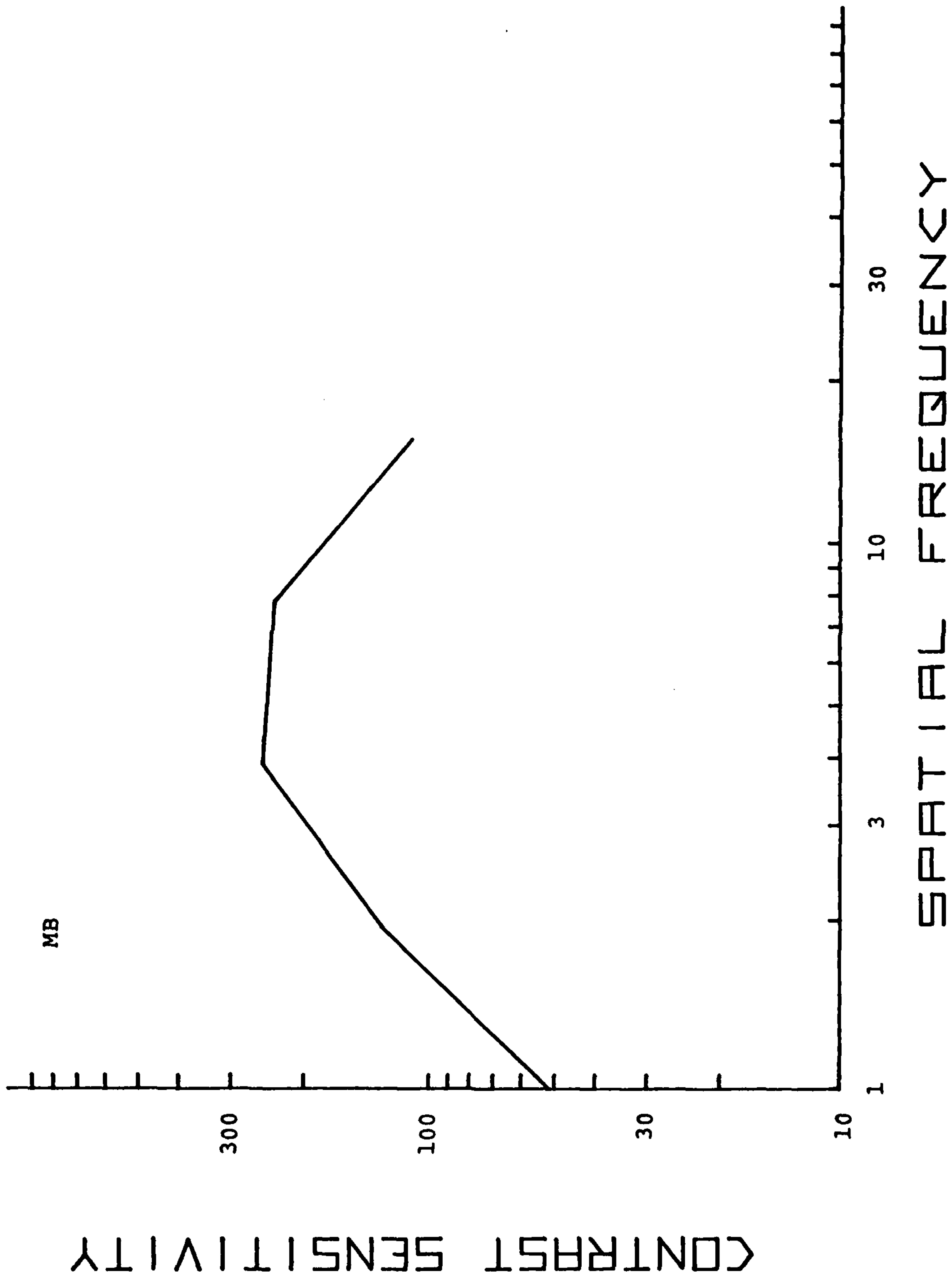
## A. Results Obtained with Sine-Wave Gratings.

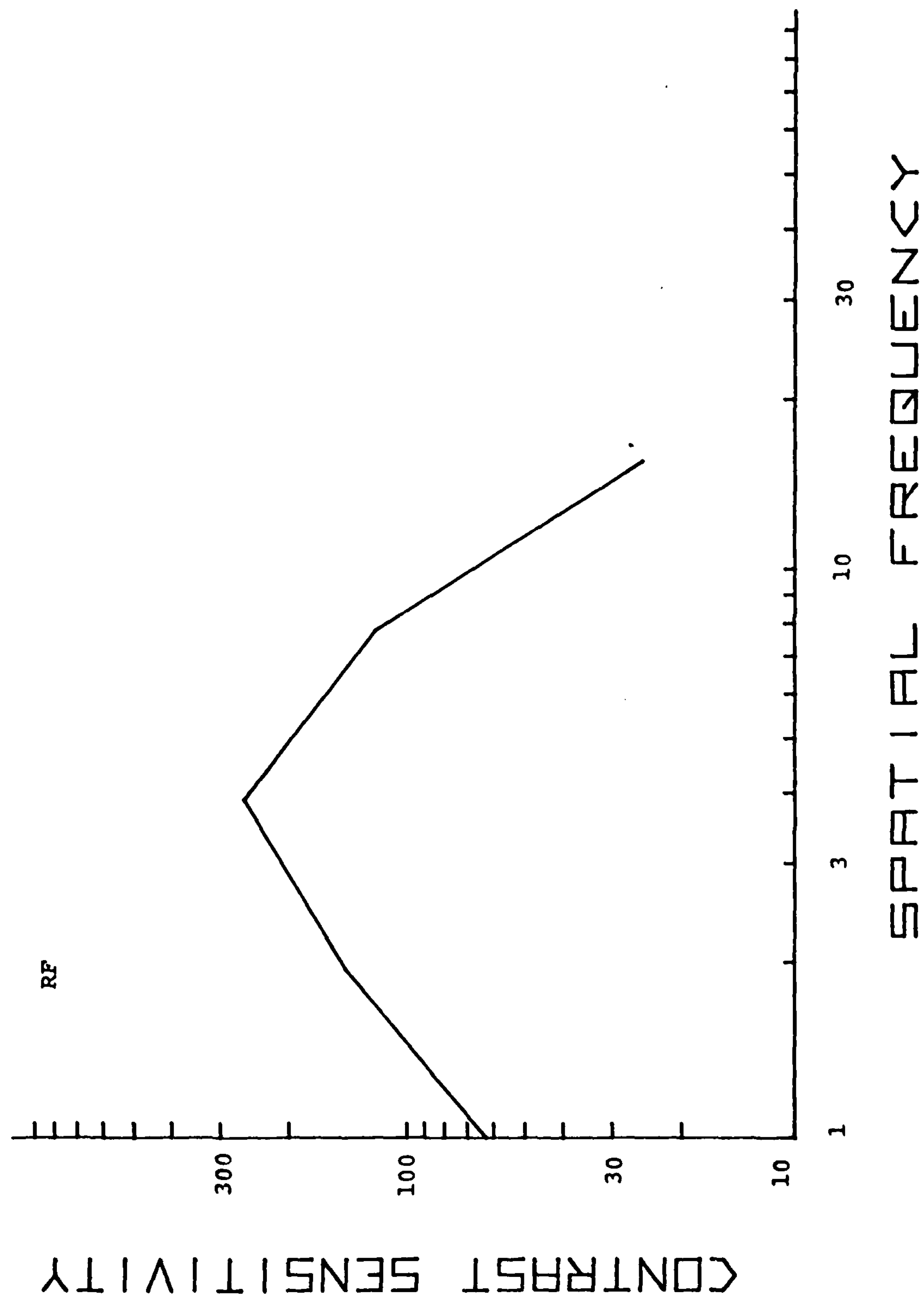
Each of the five observers set ten contrast thresholds at each of five spatial frequencies: 1, 2, 4, 8, and 16 cycles/degree. Each of figures 6 through 10 shows the contrast sensitivity function (sensitivity = 1/contrast threshold) for a given observer. Each data point in a figure is the mean of 10 threshold estimates. Standard deviations were generally about 9%, being somewhat higher for the 16-cycles/degree gratings. Figures 6 through 10 show functions based upon detection thresholds only. It was our observation that for most presentations of stationary gratings the stimulus was identifiable at its detection threshold.

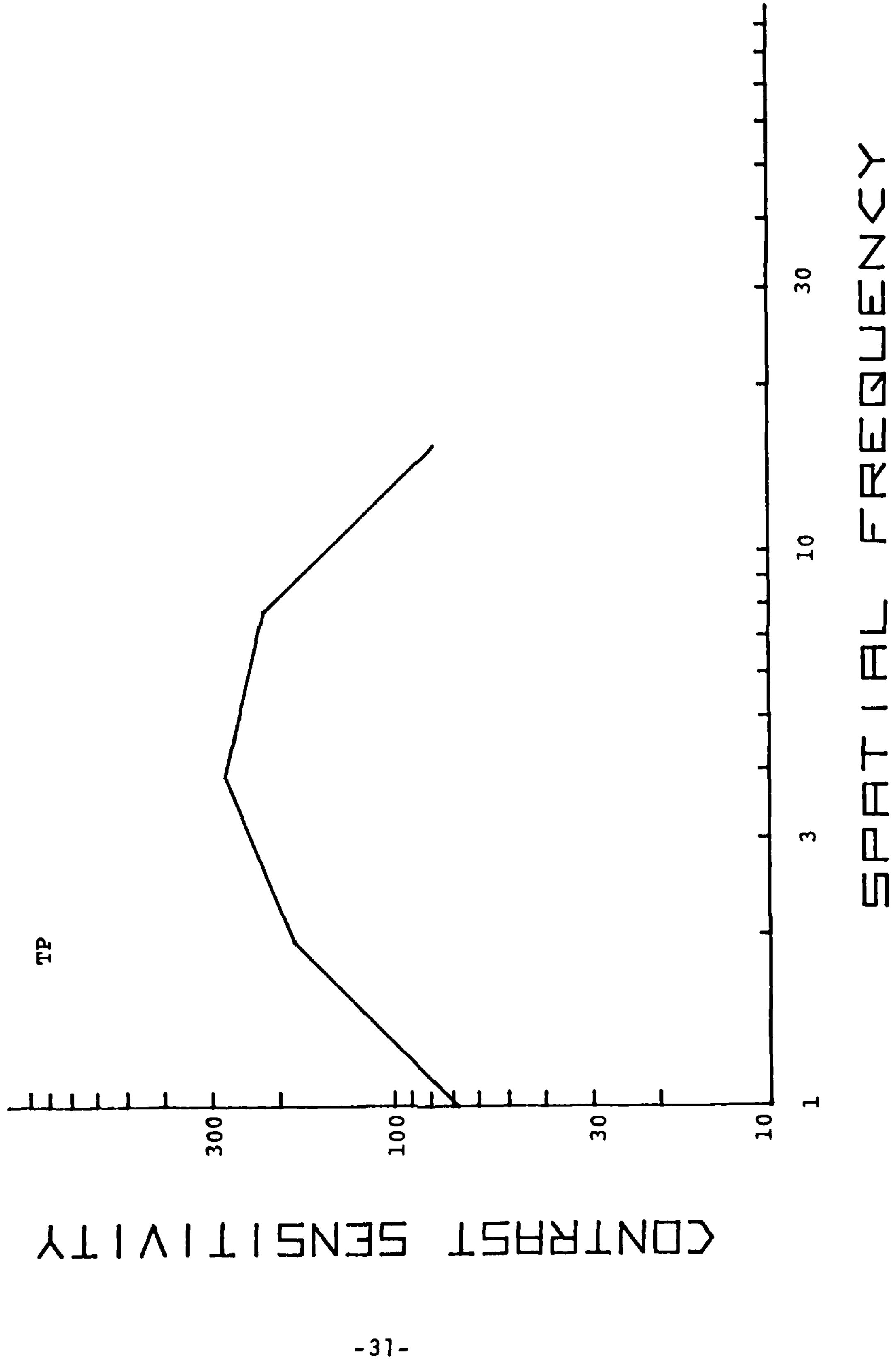
CSFs were normal for observers MM, MB, RF, and TP (Figures 6 through 9). These observers showed peak sensitivities around 3-4 cycles/degree, sharp high-frequency cutoffs, and some (normal) low-frequency attentuation. However the CSF for observer MS was quite different (see Figure 10). First, MS was less sensitive than the other observers at all spatial frequencies, except when compared to RF at the highest

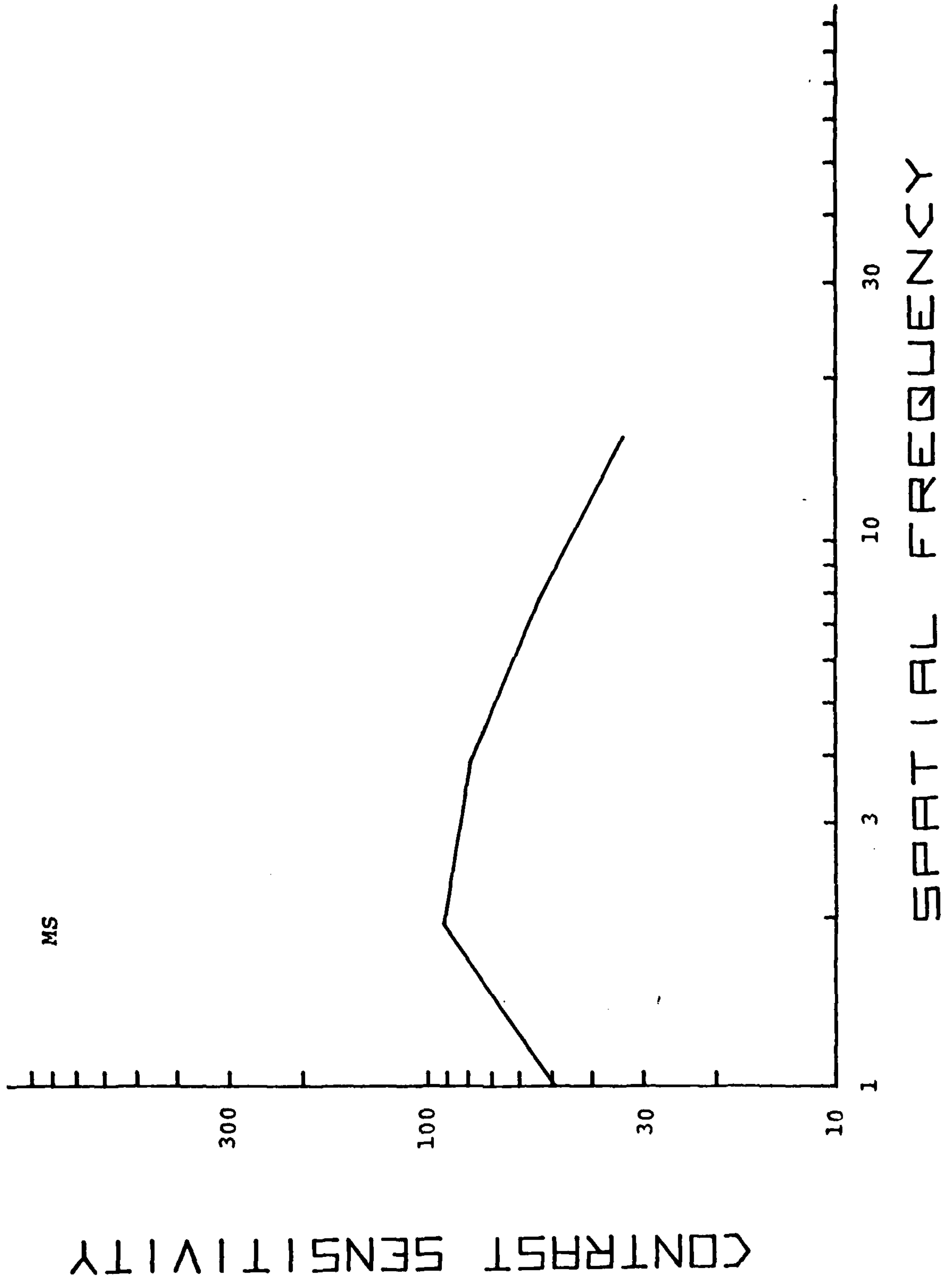
FIGURES 6-10: Contrast sensitivity functions (CSFs) in response to stationary gratings for five observers. Spatial frequency, in cycles/degree, is on the abcissa; contrast sensitivity (1/contrast threshold), on the ordinate. Figure 6: Observer MM; Figure 7, MB; Figure 8, RF; Figure 9, TP; Figure 10, MS.


MM
CONTRAST SENSITIVITY
300
100
30
10
1
3
10
30
SPATIAL FREQUENCY


MB
300
100
30
10
1
3
10
30
CONTRAST SENSITIVITY
SPATIAL FREQUENCY


RF
CONTRAST SENSITIVITY
10
30
100
300
SPATIAL FREQUENCY
1
3
10
30


CONTRAST SENSITIVITY
300
100
30
10
TP
SPATIAL FREQUENCY
1
3
10
30


MS
CONTRAST SENSITIVITY
300
100
30
10
1
3
10
30
SPATIAL FREQUENCY

spatial frequency. Second, MS had a peak sensitivity at only 2 cycles/degree. Third, MS showed an earlier and more gradual high-frequency cutoff than did the other observers, with the possible exception of MB. MS's CSF is highlighted for two reasons: First, MS showed a Snellen acuity of 20/20, perhaps because his sensitivity to high spatial frequencies approached normal levels (cf. Ginsburg, 1978). Second, in view of his abnormal CSF, MS's thresholds with Snellen-letter stimuli will be of interest, especially when compared to the thresholds of the observers with more normal CSFs.

B. Results obtained with Snellen-letter stimuli.

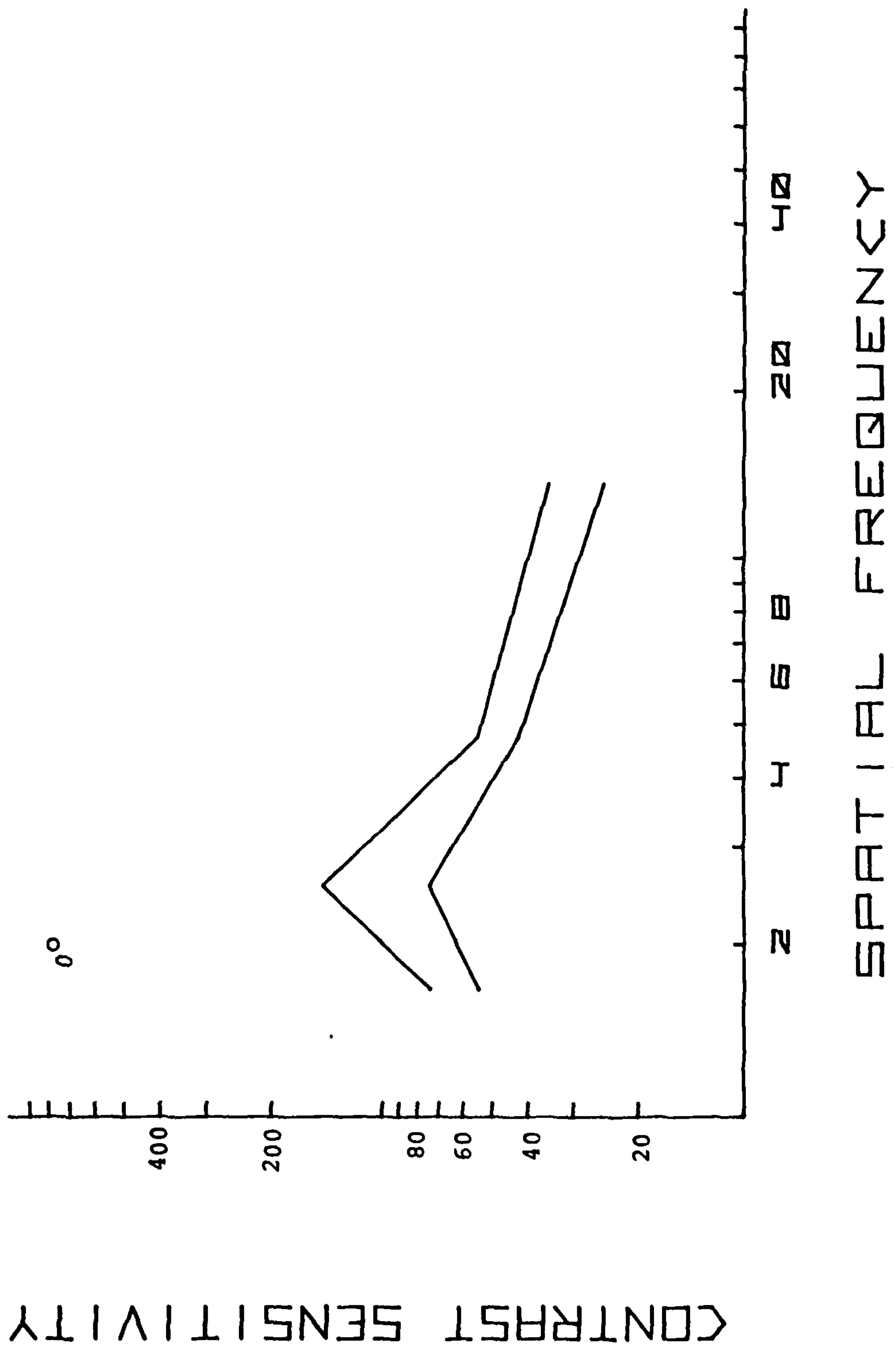
In three separate experiments, we examined the effects of a) letter size (i.e., fundamental spatial frequency), and b) letter rotation relative to the observer's frontoparallel plane on detection and identification contrast thresholds. The results are expressed in terms of contrast sensitivity.

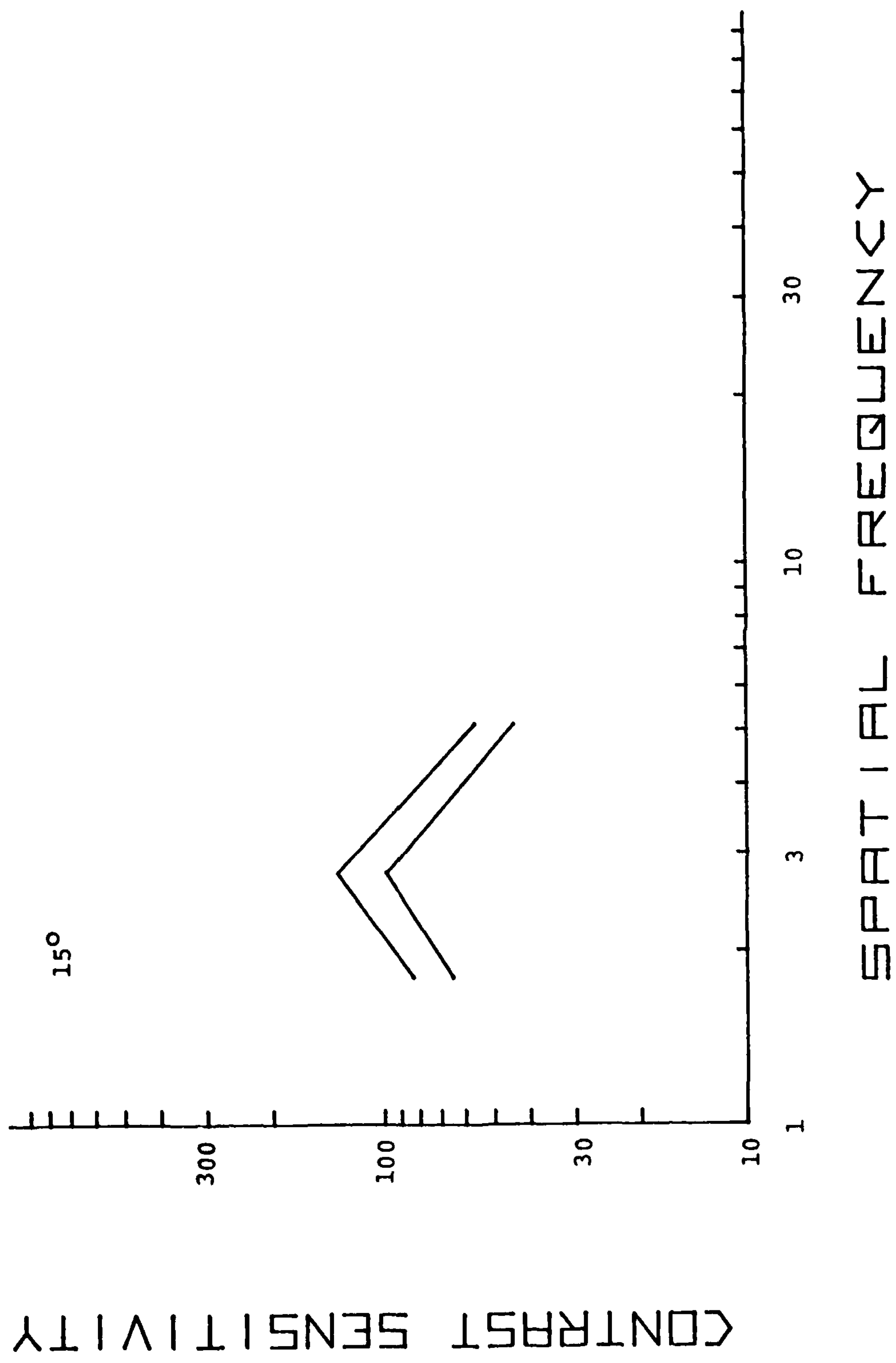
1. Effects of letter size

Figure 11 shows the effect of the fundamental spatial frequency of various letters on their detection (upper curve) and recognition (lower curve) contrast sensitivity. The curves show the mean contrast sensitivities of all five observers and are representative of the individual sensitivity functions obtained from the four observers with normal CSFs. The letters used to obtain these data had a 0° rotation and therefore shared the same fundamental frequency in both the vertical and horizontal dimensions.

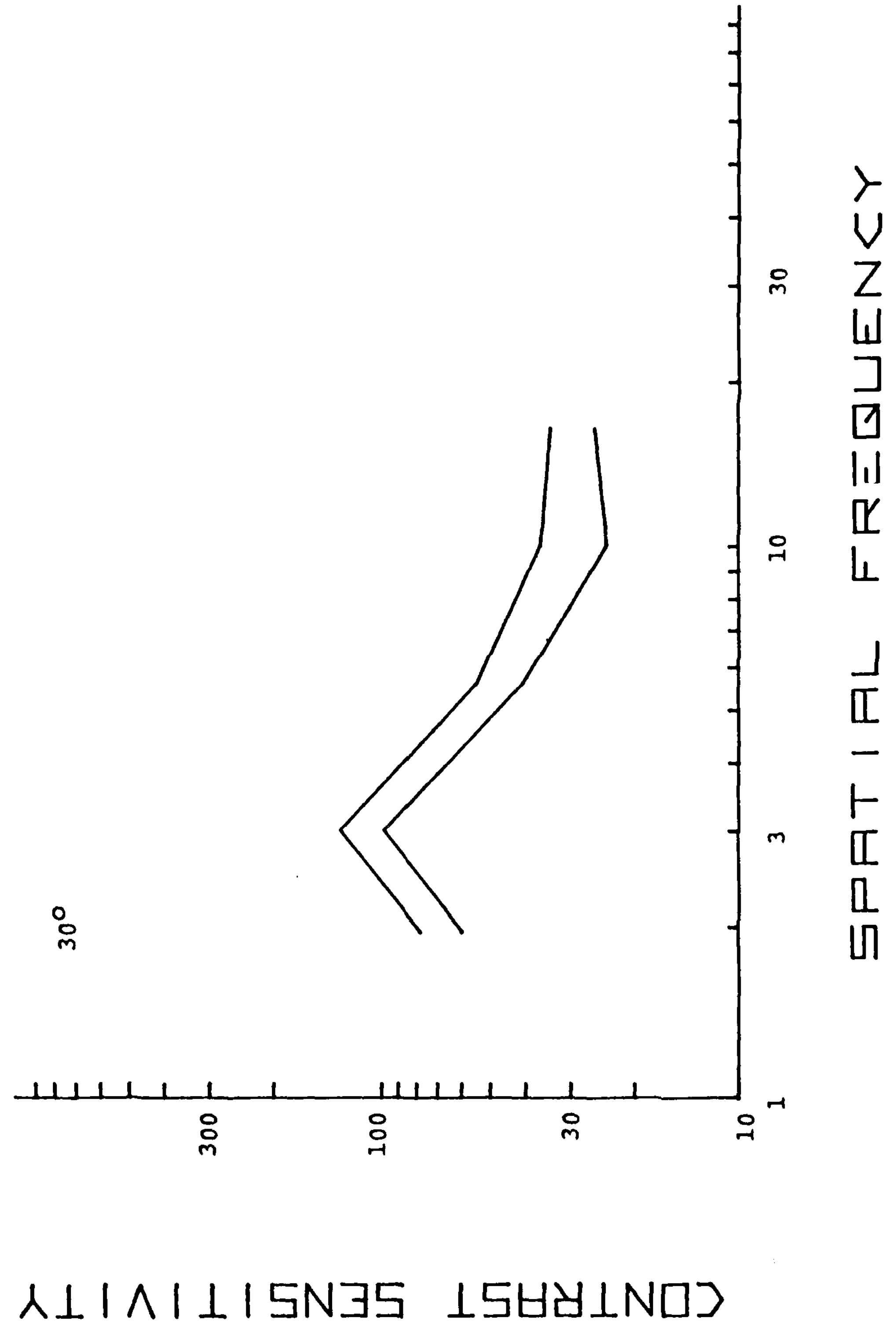
In each function of Figure 11 there is a clear and

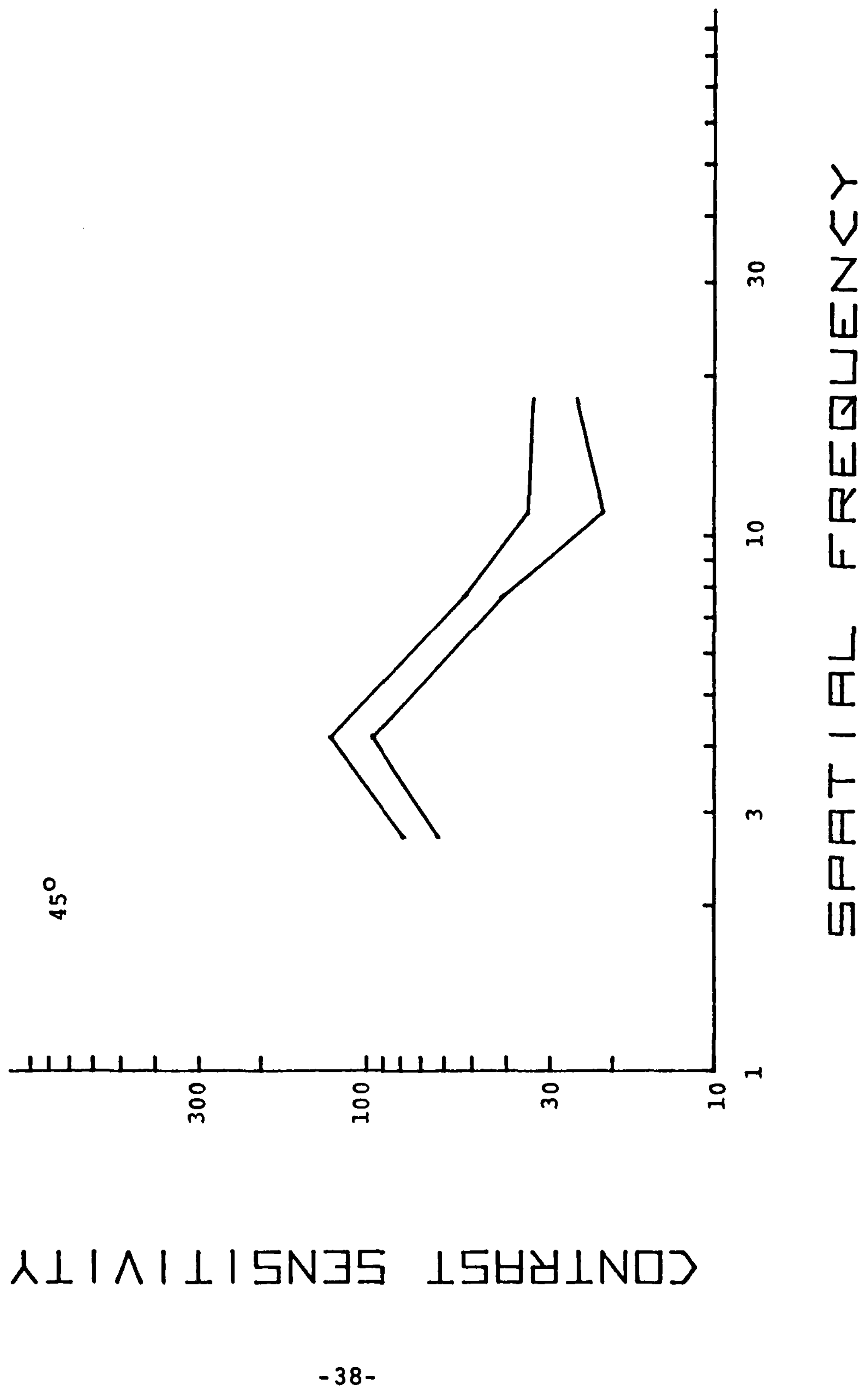
FIGURES 11-16: Contrast sensitivity (averaged over letters) for Snellen-letter detection and identification as a function of fundamental spatial frequency (in cycles/degree) at each of six different rotations of the stimuli relative to the observer's frontoparallel plane. In each figure detection sensitivity is represented in the upper curve; identification sensitivity, in the lower. Figure 11: Sensitivities at 0° rotation of the stimuli; Figure 12: Sensitivities at 15° rotation; Figure 13: at 30° rotation; Figure 14: at 45°; Figure 15: 60°; Figure 16: 75°. Curves show the averages of all five observers.

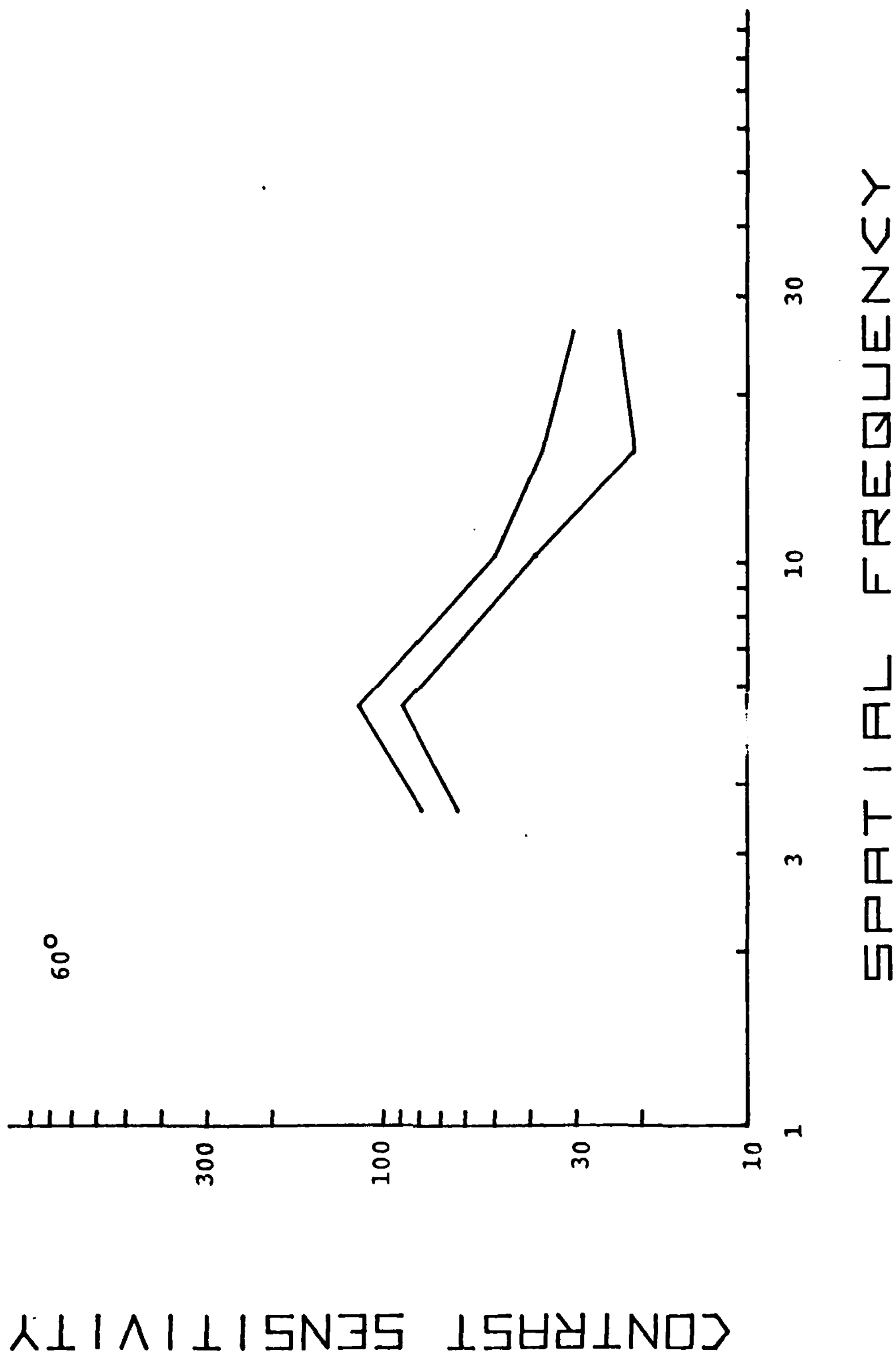

0°
CONTRAST SENSITIVITY
400
200
80
60
40
20
SPATIAL FREQUENCY
2
4
6
8
20
40

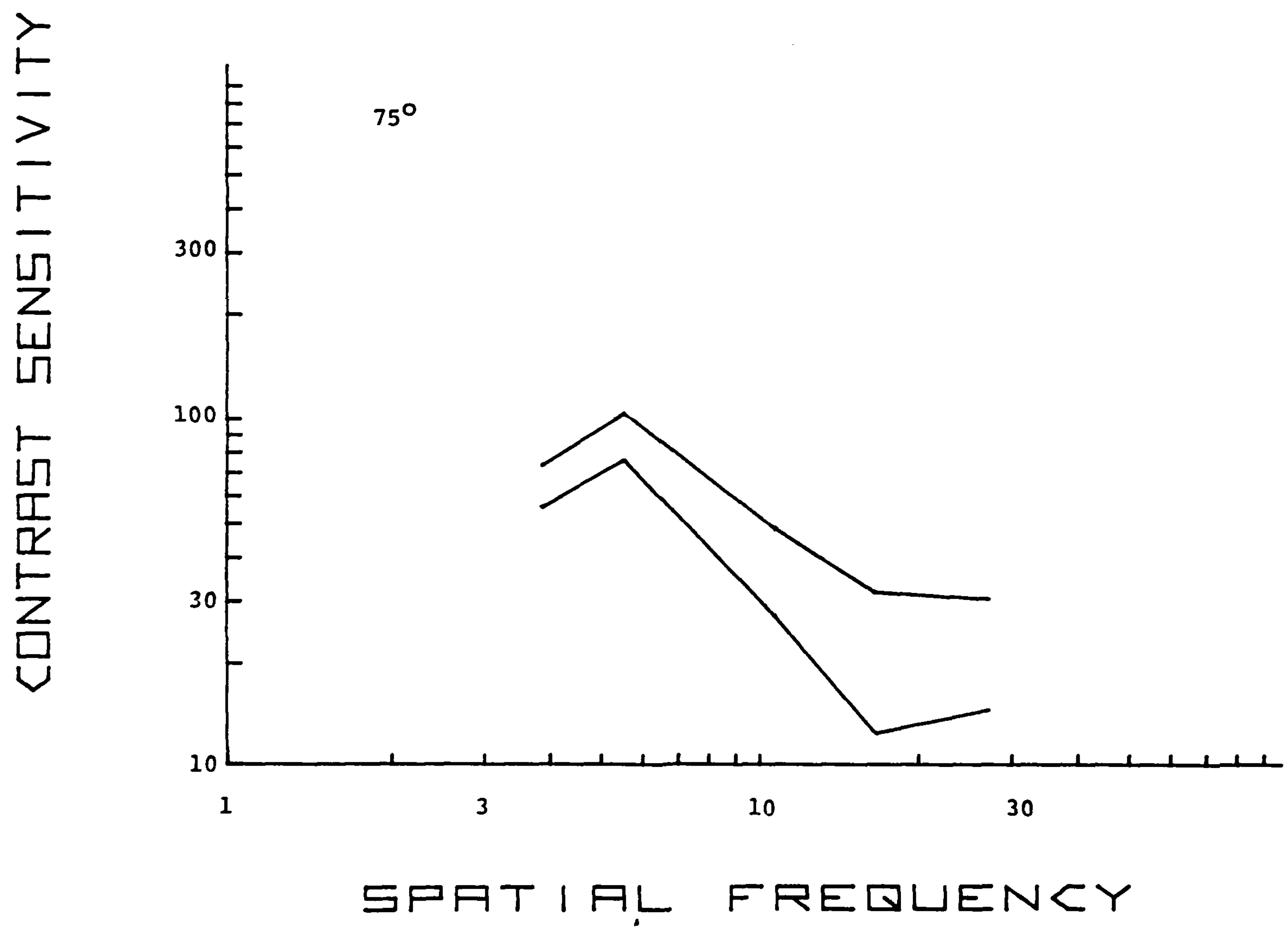


15°
300
100
30
10
1
3
10
30
SPATIAL FREQUENCY
CONTRAST SENSITIVITY


30°
CONTRAST SENSITIVITY
300
100
30
10
1
3
10
30
SPATIAL FREQUENCY


45°
CONTRAST SENSITIVITY
10
30
100
300
SPATIAL FREQUENCY
1
3
10
30


60°
CONTRAST SENSITIVITY
10
30
100
300
SPATIAL FREQUENCY
1
3
10
30


CONTRAST SENSITIVITY
75°
300
100
30
10
1
3
10
30
SPATIAL FREQUENCY

significant peak at 2.6 cycles/degree, nearing the peak of the normal CSF. This peak is followed by a rapid decline in sensitivity for stimuli with higher fundamental frequencies. The sensitivity for the 4.89-cycles/degree stimuli is lower than would be expected on the basis of the normal CSFs alone. Much of the group's loss of sensitivity at 4.89 cycles/degree can be attributed to MS's comparatively low sensitivity (see Figure 18). The remainder of this effect may be attributed to uncertainty and overcompensation on the parts of the observers. Alternatively, detection of the letters may not be solely mediated by detection of the fundamental spatial frequencies of the letters as suggested by Ginsburg (1978).

The curves shown in Figure 11 differ from Ginsburg's in that there is an almost constant difference on log-log axes between the sensitivities for detection and recognition at all spatial frequencies. On the other hand, Ginsburg found that detection and identification sensitivity were nearly equal for stimuli with very low fundamental spatial frequencies (about 1 cycle/degree) and gradually diverged as fundamental spatial frequency increased, with the sensitivity for identification declining more rapidly than the sensitivity for detection. The explanation for Ginsburg's finding was that identification requires that frequencies 1.5-2.5 times higher than the fundamental reach their thresholds. Since the normal CSF shows a falloff for high frequencies, identification sensitivity should decline rapidly as fundamental spatial frequency is increased.

Our results, which were the same regardless of the procedure used to gather the data, suggest that observers may have used frequencies less than 1.5 times the fundamental for identification. These results are also consistent with the findings of Petersik (1980).

Table 1 shows the extent of agreement between the predicted contrast sensitivity to letters of various sizes (based upon Ginsburg's model) and the obtained contrast sensitivity for those same letters. Row 1 shows the fundamental spatial frequency for each of the Snellen-letter stimuli at 0° rotation. Row 2 shows the spatial frequency assumed by Ginsburg's model to be required for identification. In practice, it is 2.0 (i.e., midway between 1.5 and 2.5) times the fundamental spatial frequency. Row 3 shows the group's predicted identification contrast sensitivity to the frequency shown in row 2. This figure is based on linear interpolation of each observer's CSF. Row 4 shows the obtained identification sensitivity for the stimuli having the fundamental frequencies listed in row 1, and row 5 shows the difference between predicted and obtained values. Row 6 presents the obtained value as a percentage of the predicted value. (Rows 7-10 present similar information for observer MS.)

As can be seen in Table 1, for the three lowest spatial frequencies the obtained identification contrast sensitivity was a nearly constant percentage (.28-.37) of the predicted sensitivity. Given the differences in equipment and stimuli used to make the predictions and obtain the

TABLE 1

Contrast Sensitivities Predicted by Ginsburg's Model

and Obtained in Experiment 1

| | | | | |
|---|---|---|---|---|
| Fundamental frequency (cycles/degree) | 1.71 | 2.63 | 4.89 | 14.02 |
| Frequency used for recognition (cycles/degree) | 3.4 | 5.3 | 9.8 | 28.0 |
| Predicted Sensitivity of group | 196.8 | 200.2 | 118.4 | 41.4 |
| Obtained Sensitivity of group | 54.9 | 73.8 | 40.3 | 24.9 |
| Difference | 141.9 | 126.4 | 78.1 | 16.5 |
| Percent Difference | .28 | .37 | .34 | .60 |
| Predicted Sensitivity for MS | 92.0 | 66.0 | 45.0 | 21.5 |
| Obtained Sensitivity for MS | 38.2 | 48.2 | 27.7 | 15.1 |
| Difference | 53.8 | 17.8 | 17.3 | 6.4 |
| Percent Difference | .42 | .73 | .62 | .70 |

thresholds, such a discrepancy between predicted and obtained values should not be considered damaging to the model that generated the predictions as long as the obtained sensitivities are nearly constant percentages of the predicted values. The relationship between predicted and obtained identification sensitivities does deviate for the smallest stimuli (14.02 cycles/degree), but in this case the frequencies needed for identification (around 28.04 cycles/degree) are nearing the resolution limits of the human visual system and therefore it is not too surprising to find the identification sensitivity obtained with Snellen-letter stimuli more closely match the prediction derived from the CSFs.

The model did a much better job of predicting the identification contrast sensitivity of observer MS (bottom half of Table 1). In this case, the obtained values are large and nearly constant percentages of the predicted values, especially for the three highest spatial frequencies. Recall that MS showed an abnormal CSF despite the fact that he scored 20/20 on a conventional Snellen acuity test. (Figures 19 through 23 show additional contrast sensitivities of observer MS. Further discussion of these data appears in a later section.) The results of this study confirm that the CSF can accurately predict the pattern of results on a complex spatial recognition task. In order to refine the predictions made, we need to know more precisely the spatial frequencies required for the identification of Snellen letters of various sizes.

It should be noted here that in no cases were detection or identification contrast sensitivities the greatest for the <u>largest</u> letters tested (cf. Figures 11 through 16). This finding is contrary to the general belief that the larger the object, the easier it is to see. On the other hand, this finding is predicted on the basis of the low-frequency falloff seen in the normal CSF under ordinary unrestrained viewing conditions.

Table 2 shows the contrast sensitivities obtained with each of the Snellen letters used in this stage of the study. These values are collapsed over spatial frequency. The letters in Table 1 are arranged in order of decreasing energy (i.e., B, E, V, and L). The pattern of results demonstrates that for both the detection and identification tasks, contrast sensitivity monotonically decreases as energy decreases. This finding is in correspondence with some of the results of Petersik (1980) and confirms that performance on a psychological task like the identification of complex stimuli can be related to a knowledge of the physical properties of the stimuli.

Table 2

Group Contrast Sensitivities for Each Snellen Letter

| | Letter | | | |
|---|---|---|---|---|
| | B | E | V | L |
| Detection sensitivity | 70.51 | 69.18 | 66.45 | 64.29 |
| Identification sensitivity | 49.14 | 48.50 | 48.08 | 47.51 |

## 2. Effects of rotation

Figures 11 through 16 show, for each of the six rotations, mean contrast sensitivity of the group as a function of the fundamental spatial frequency of the Snellen-letter stimuli. In each figure, the upper curve shows sensitivity based upon detection thresholds whereas the lower curve shows sensitivity based upon identification thresholds. Each data point is collapsed over the four Snellen letters tested and is the mean of 40 threshold settings, eight for each observer. The curves in Figures 11 through 16 are representative of the individual functions obtained from each of the four observers with normal CSFs.

The abcissa in each of these figures shows the fundamental spatial frequency corresponding to the stroke widths of Snellen letters of various sizes. Notice that for each successive rotation (each successive figure), the distribution of relevant spatial frequencies shifts to the right, i.e., toward higher frequencies. This is due to the projective forshortening of spatial information in the horizontal dimension produced by rotation of the letters.

For each rotation, the curves for both detection and identification sensitivity show a peak at the second-largest letter size (i.e., at the second lowest fundamental spatial frequency), irrespective of its absolute value in terms of spatial frequency. For example, at 0° rotation Snellen letters with fundamental spatial frequencies of 2.63 cycles/ degree yielded a detection sensitivity of 140, those with

fundamental spatial frequencies of 4.89 cycles/degree, 53. On the other hand, at 45° rotation sensitivity to letters with fundamental frequencies of 4.30 cycles/degree far exceeded sensitivity to letters with fundamental frequencies of 2.8 cycles/degree (123 vs. 78)---just the opposite of the relationship between these frequencies at 0° rotation.

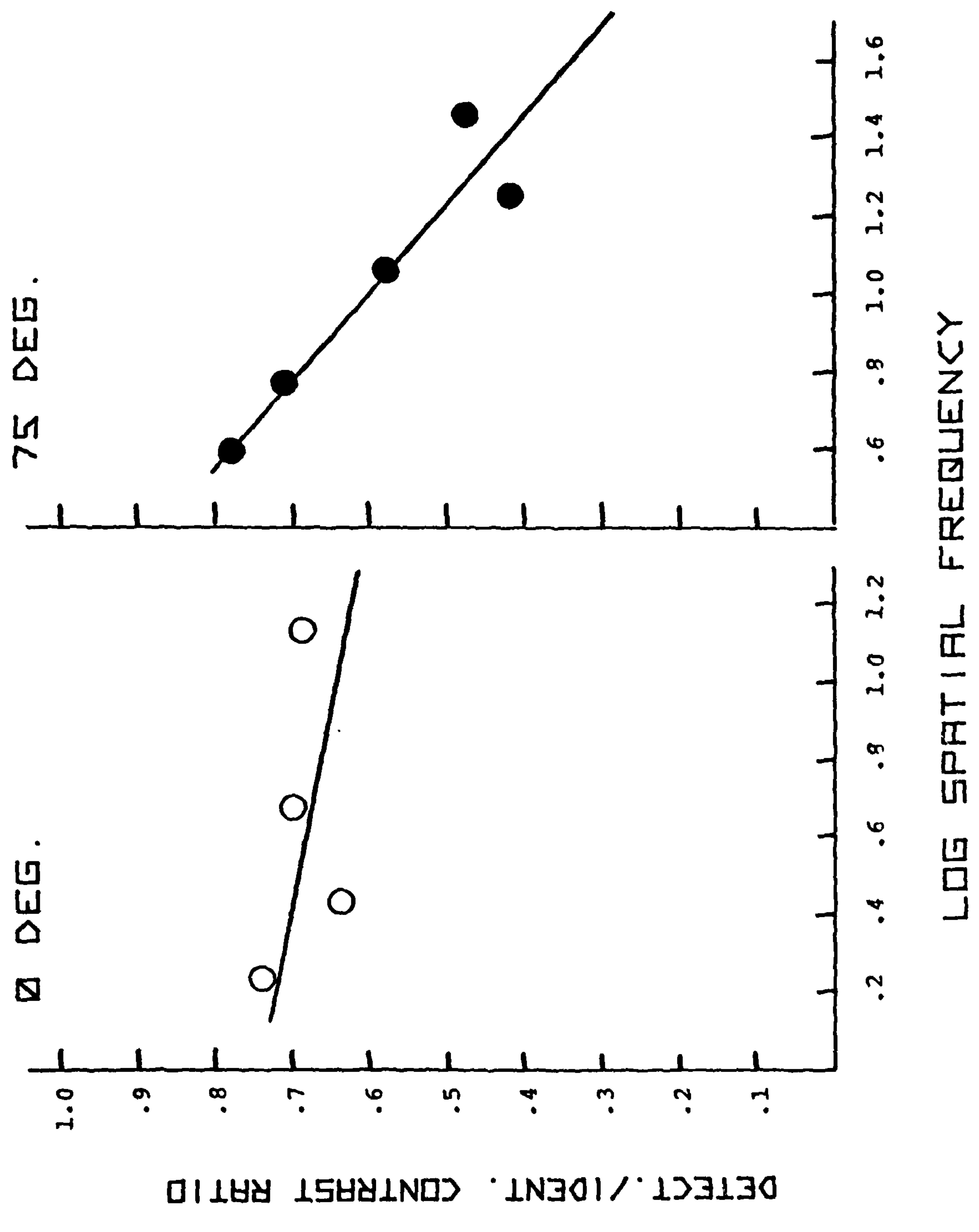
We believe that the discrepancy in these results may be accounted for by the fact that as stimuli rotate around the vertical axis, projective information in the horizontal dimension changes proportionally with the degree of rotation whereas projective information in the vertical dimension does not change at all. The constant shape of our functions over rotations indicates that observers made use of at least some information in the vertical dimension on both detection and identification tasks. The particular shape of the function, therefore, must reflect information being used in both the vertical and horizontal dimensions.

Another finding apparent in Figures 11 through 16 is that beyond 30° rotation the decline in sensitivity beyond the peak spatial frequency is more rapid for identification than for detection. Hence the curves begin to diverge beyond the peak frequency, with the curve for identification dropping off more rapidly, and this divergence is greater for each successive rotation beyond 30°. This suggests that either a) with greater rotation the information available for identification becomes attenuated, or

b) with greater rotation the information required for identification becomes shifted to higher spatial frequencies which require more contrast to reach threshold (because of the sharp falloff at high spatial frequencies in the normal CSF).

In order to more clearly demonstrate this shift in identification sensitivity relative to detection sensitivity, we plotted the detection-to-identification contrast threshold ratio as a function of fundamental spatial frequency for a number of different letters at different rotations. Figure 17 shows a typical result for the letter B at two rotations. As can be seen in the figure, at 0° rotation detection threshold is a nearly constant percentage of the identification threshold (i.e., the slope of the function is very shallow; Slope = -.88). This finding supports our earlier suggestion that for letters at 0° rotation, our observers made identifications based upon frequency information less than 1.5 times the fundamental. On the other hand, at 75° rotation, the detection/identification threshold contrast ratio changes relatively dramatically as a function of spatial frequency. At 75°, the slope of the function is -.43, greater than the slope at 0° rotation by almost a factor of five.

FIGURE 17: The detection-to-identification threshold contrast ratio as a function of log spatial frequency (in cycles/degree) for five observers. Left panel: results obtained with stimuli rotated to 0°; right panel: results obtained with stimuli rotated to 75°. Solid lines are regression lines obtained in a least-squares analysis.



Ø DEG.
75 DEG.
DETECT./IDENT. CONTRAST RATIO
LOG SPATIAL FREQUENCY
1.0
.9
.8
.7
.6
.5
.4
.3
.2
.1
.2
.4
.6
.8
1.0
1.2
1.4
1.6

According to Ginsburg (1978), we obtain straight-line functions in Figure 17 because

> . . . the contrast sensitivity function decreases exponentially from peak to minimum sensitivity with increasing spatial frequency when plotted on log contrast sensitivity versus log spatial frequency scale. If the ratio of spatial frequencies used for the detection and identification of Snellen letters remains the same for all different size letters and the detection and identification thresholds are a function of the shape of the contrast sensitivity function, then the ratio should be a straight line when plotted on a linear ratio versus log spatial frequency scale.

Assuming Ginsburg's comments to be correct, the implications of the findings presented in Figure 17 are: 1) at both 0° and 75° rotation of Snellen-letter stimuli, the ratio of <u>spatial frequencies</u> used for the detection and identification of letters is constant, and 2) the specific ratio of spatial frequencies used for the detection and identification of letters differs for 0°-letters versus 75°-letters; specifically, in our experiment, at 0° identification occurs at frequencies less than 1.5 times the fundamental frequency while at 75° it occurs at roughly 1.5-2.5 times the fundamental (because our plot at 75° is similar to the one presented by Ginsburg, 1978).

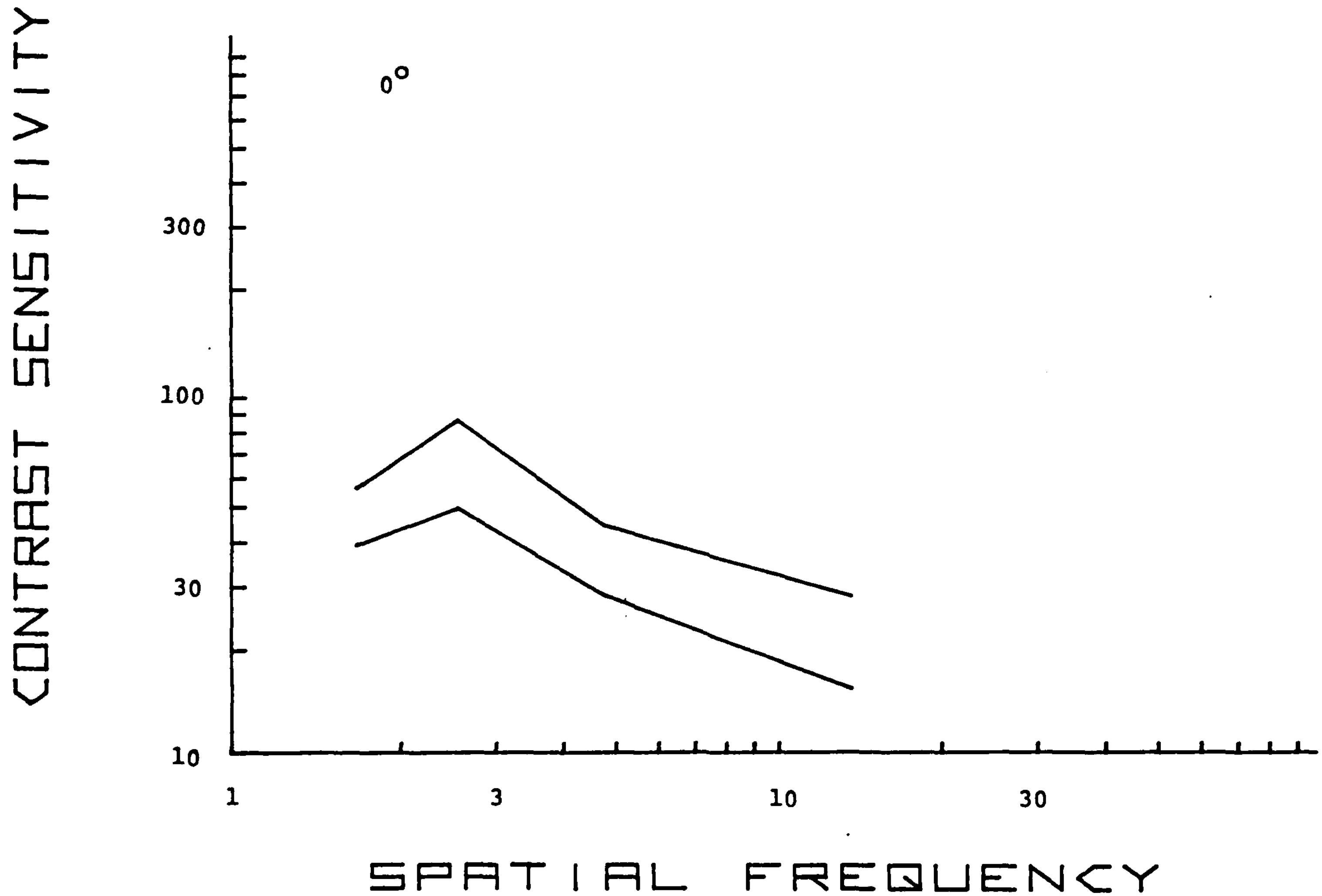
In support of the above interpretation, we plotted both detection and identification contrast sensitivity as a function of linear spatial frequency. Regression lines were next determined. Correlation coefficients (r) for the group were never lower than 0.80. Finally, we determined the ratio of the spatial-frequency intercept for

detection sensitivity versus the spatial-frequency intercept for identification sensitivity as an estimate of the bandwidth of the identification-to-detection threshold ratio (see Ginsburg, 1978, p. 87, for rationale). As predicted above, we found that bandwidths were less than 1.5 (1.1) for 0°-rotation letters and were greater than 1.5 (1.6) for 75°-rotation letters. Letters at intermediate rotations had bandwidth estimates between these two extremes.

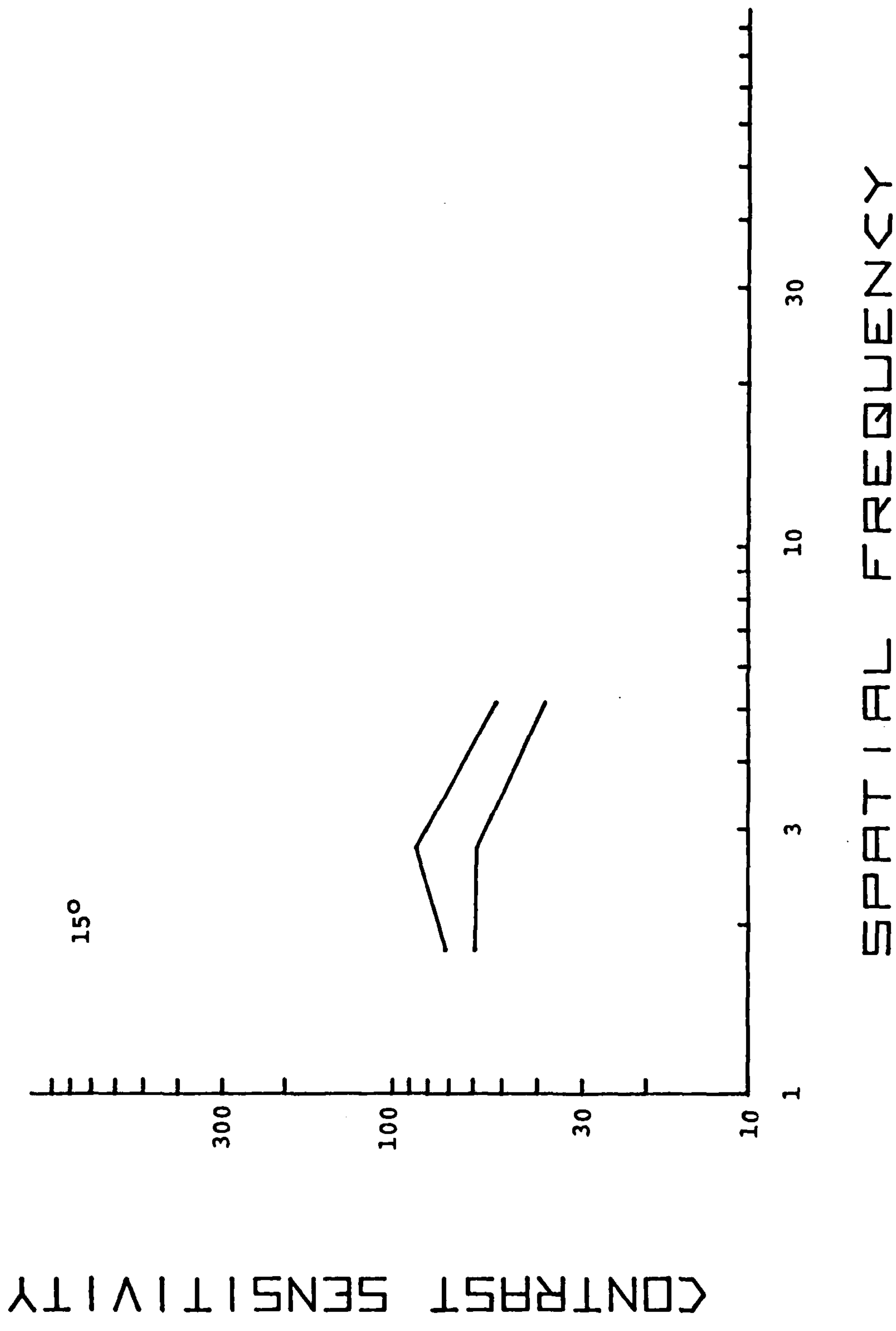
Figures 18 through 23 show the effects of rotation on the contrast sensitivities of observer MS. At 0° and 30° rotations, MS's functions appear normal and much like the curves for the group as a whole. However, by 45° the familiar peaks have begun to disappear from MS's functions, and by 60° they are absent altogether. Furthermore, MS's identification-sensitivity functions are separated from the detection-sensitivity functions by a greater magnitude than for the group as a whole. Both of these effects seem to be attributable to MS's intermediate-to-high-frequency losses. We also estimated MS's identification-to-detection threshold bandwidth by the least squares method and found it to be approximately 1.32.

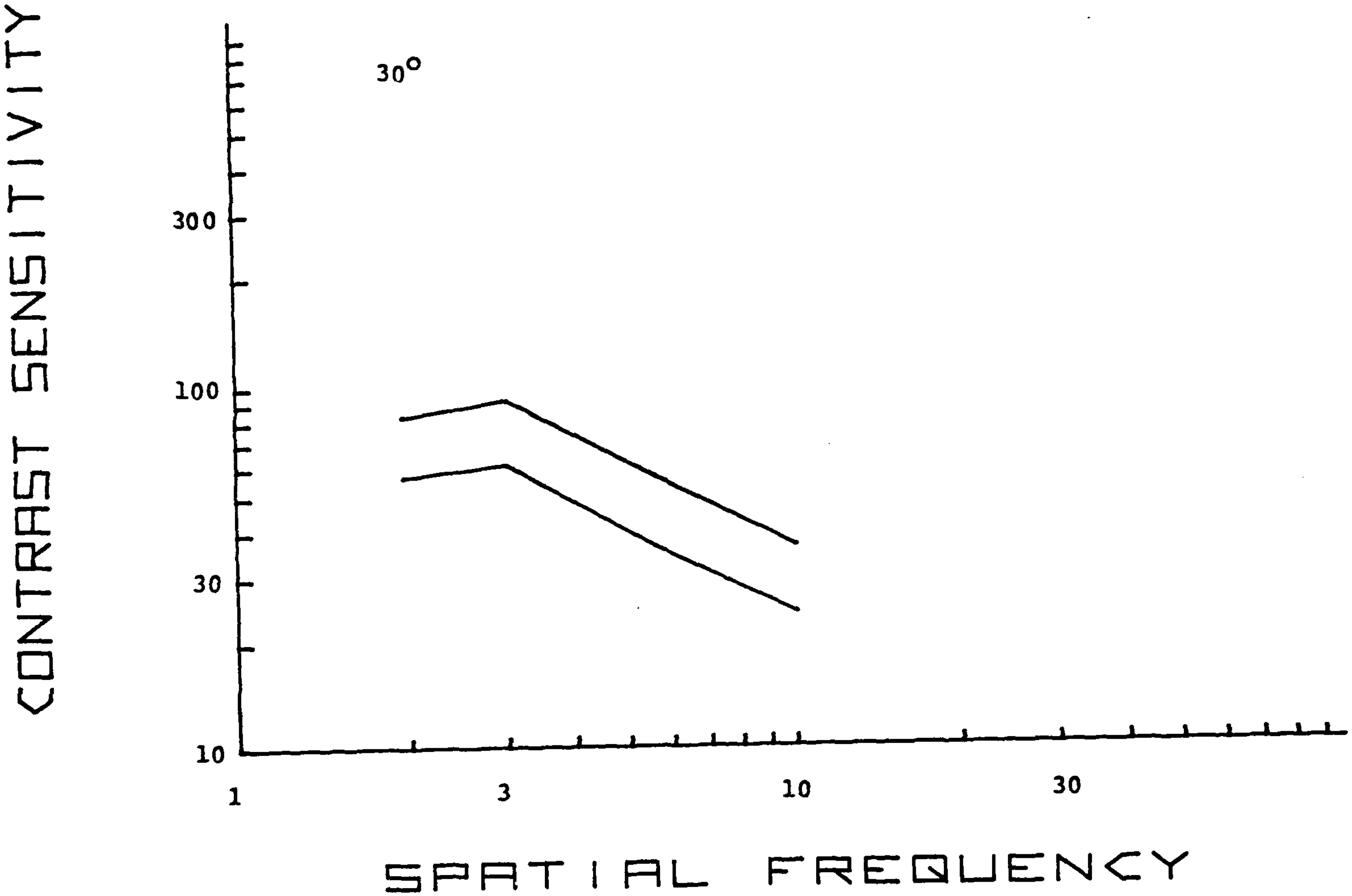
Figure 24 summarizes some of the results obtained with Snellen-letter stimuli that varied both in size and in rotation. Once again, upper curves show detection sensitivity while lower curves show the corresponding identification sensitivity. In Figure 24, the leftmost

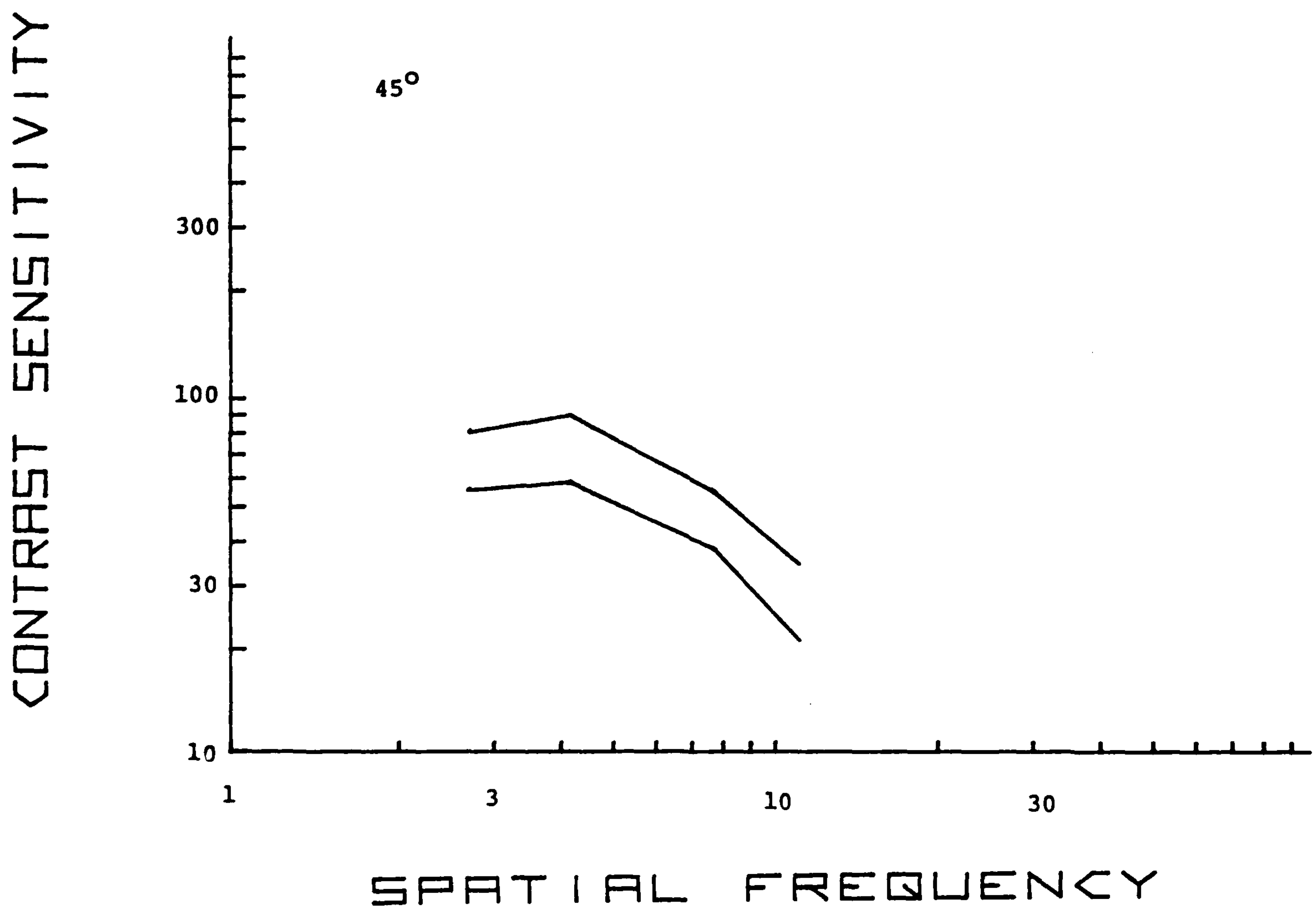
FIGURES 18-23: Contrast sensitivity (averaged over letters) for Snellen-letter detection (upper curves) and identification (lower curves) as a function of fundamental spatial frequency (in cycles/degree) at each of six different rotations of the stimuli relative to the observer's frontoparallel plane. Figures are for observer MS only. Figure 18: Sensitivities at 0° rotation of the stimuli; Figure 19: Sensitivities at 15° rotation; Figure 20: Sensitivities at 30°; Figure 21: at 45°; Figure 22: at 60°; Figure 23: at 75°.

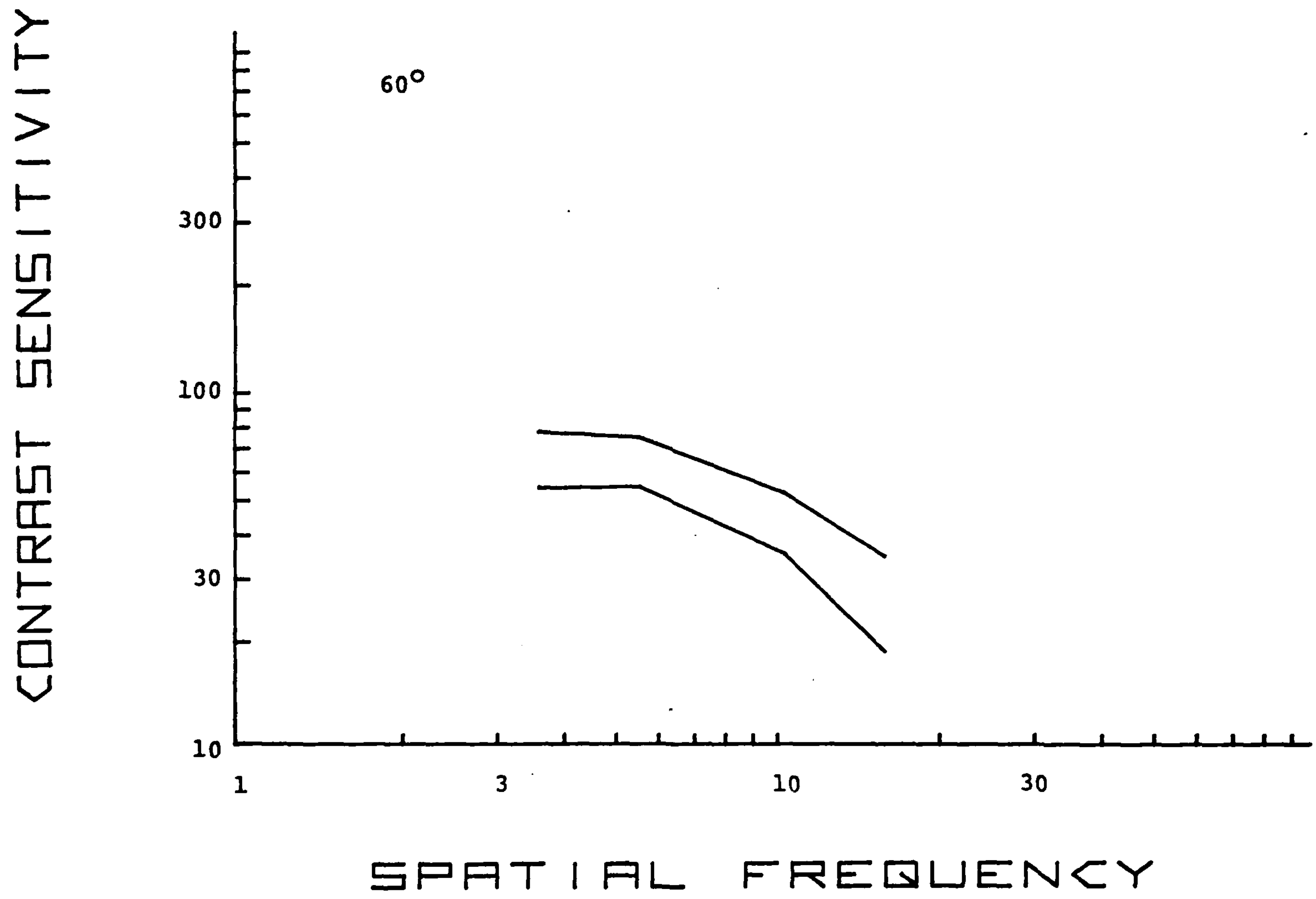


CONTRAST SENSITIVITY
300
100
30
10
1
3
10
30
SPATIAL FREQUENCY
0°


15°
CONTRAST SENSITIVITY
300
100
30
10
1
3
10
30
SPATIAL FREQUENCY


30°
CONTRAST SENSITIVITY
300
100
30
10
1
3
10
30
SPATIAL FREQUENCY


45°
300
100
30
10
1
3
10
30
CONTRAST SENSITIVITY
SPATIAL FREQUENCY


CONTRAST SENSITIVITY
60°
300
100
30
10
1
3
10
30
SPATIAL FREQUENCY

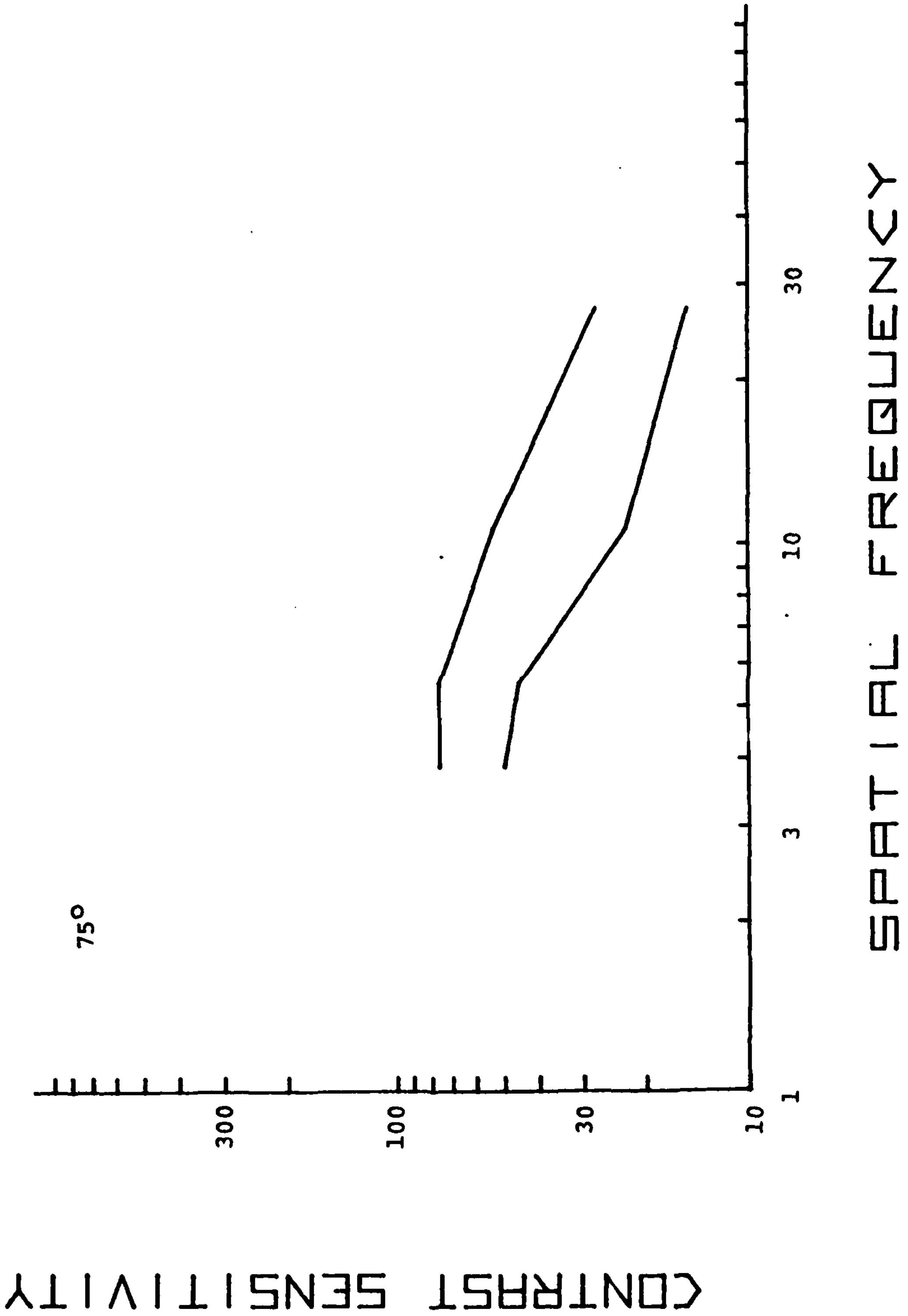
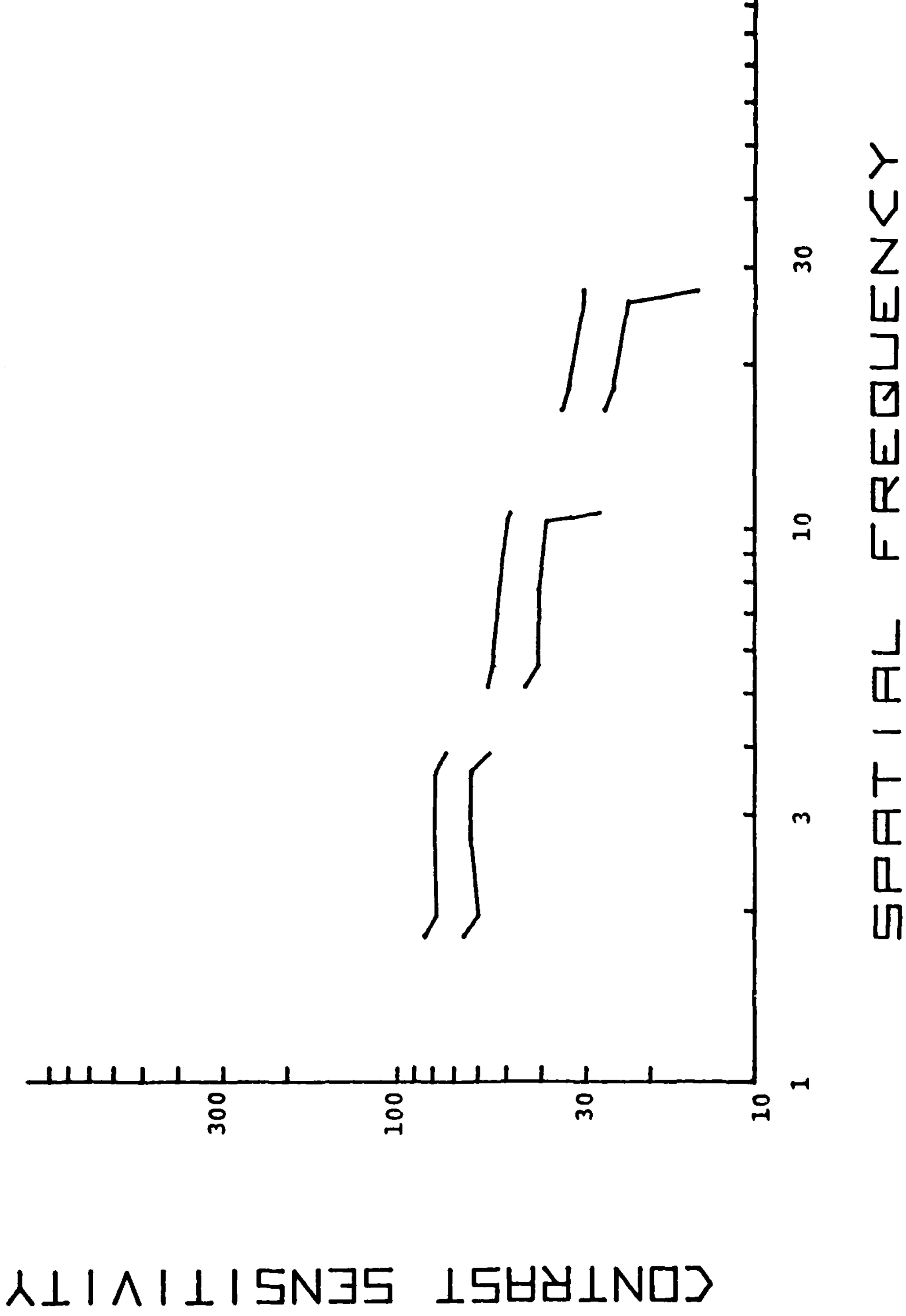

75°
CONTRAST SENSITIVITY
10
30
100
300
SPATIAL FREQUENCY
1
3
10
30

FIGURE 24: Detection (upper curves) and identification (lower curves) contrast sensitivities as functions of the size (i.e., fundamental spatial frequency) and rotation of Snellen-letter stimuli. Leftmost curves show results obtained with largest letter set; middle curves, with medium-size letter set; rightmost, with smallest letters. In each curve, data obtained with stimuli rotated 0° are shown on the left; with stimuli rotated 75°, on the right. Intermediate rotations are 15°, 30°, 45°, and 60° respectively. Data averaged over letters and observers.


CONTRAST SENSITIVITY
10
30
100
300
SPATIAL FREQUENCY
1
3
10
30

curves show the results obtained with the largest letters; the middle curves, medium sized letters; and the rightmost curves, the smallest letters. Data in each curve, progressing from left to right, show the results of rotation (15°-75°). As can be seen in the figure, for the large letters the effect of rotation was noticeable as a drop in sensitivity between 15° and 30°, and again between 60° and 75°. For the medium letters, there was a gradual decline in sensitivity with greater rotation, and identification sensitivity showed an abrupt decline at 75°. For the smallest letters, the same was true. Comparison of the sets of curves shows that each reduction in the size of the letters produced a corresponding decline in both detection and identification sensitivity. Together, variations in size and in rotation accounted for a decline in detection sensitivity of roughly two-thirds; in identification sensitivity, of almost three-fourths.

## IV. EXPERIMENTS WITH DRIFTING STIMULI

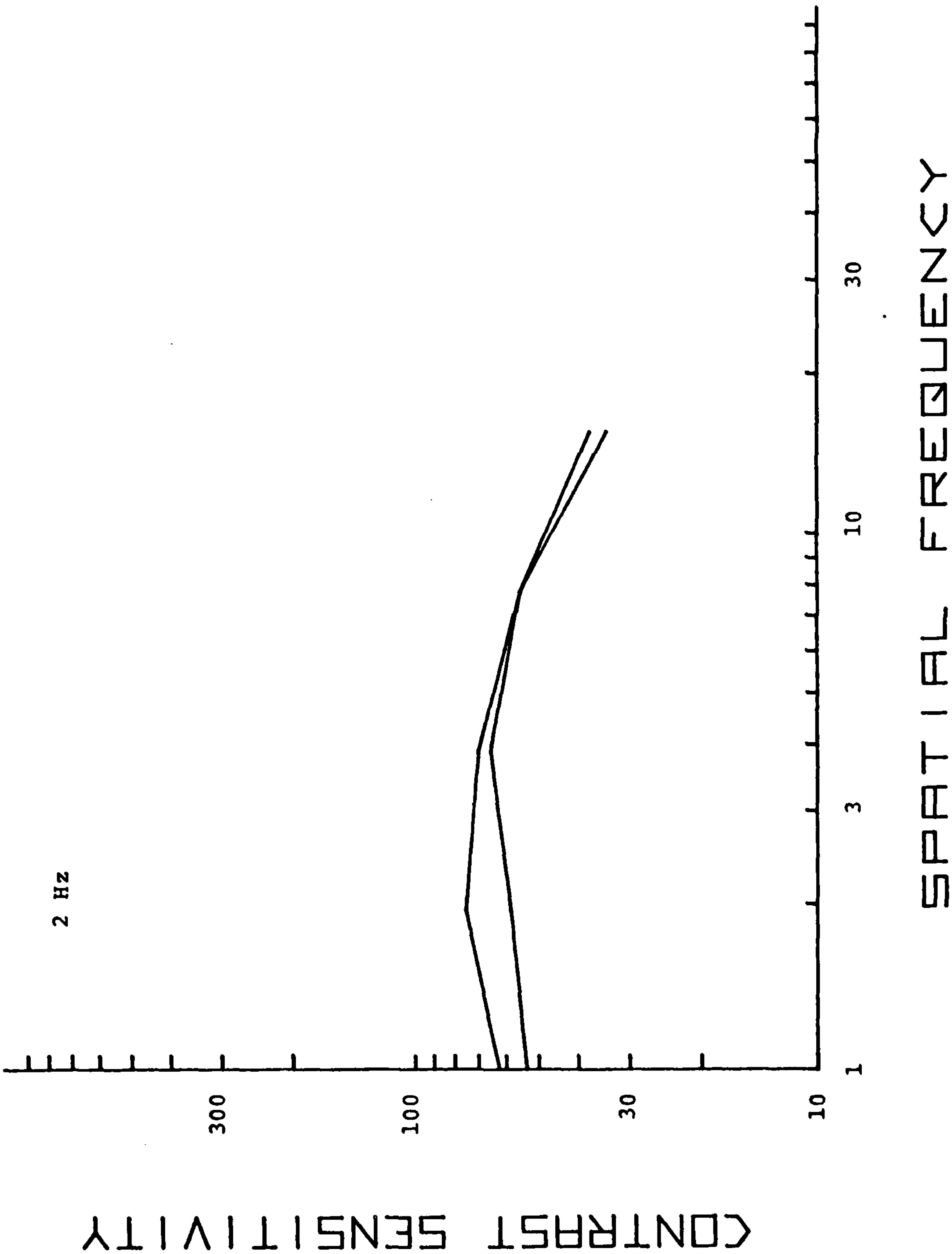
In these experiments observers adjusted both detection and identification contrast thresholds in the presence of stimuli drifting at various temporal rates. Again, observers' heads were unrestrained although head movements were minimized. Because temporal frequency is a more general way to express the rate of spatial change over time than is velocity, we express our results in terms of temporal frequency, except where noted. Where appropriate, velocities corresponding to temporal frequencies are also presented.

### A. Results Obtained with Drifting Sine-Wave Gratings

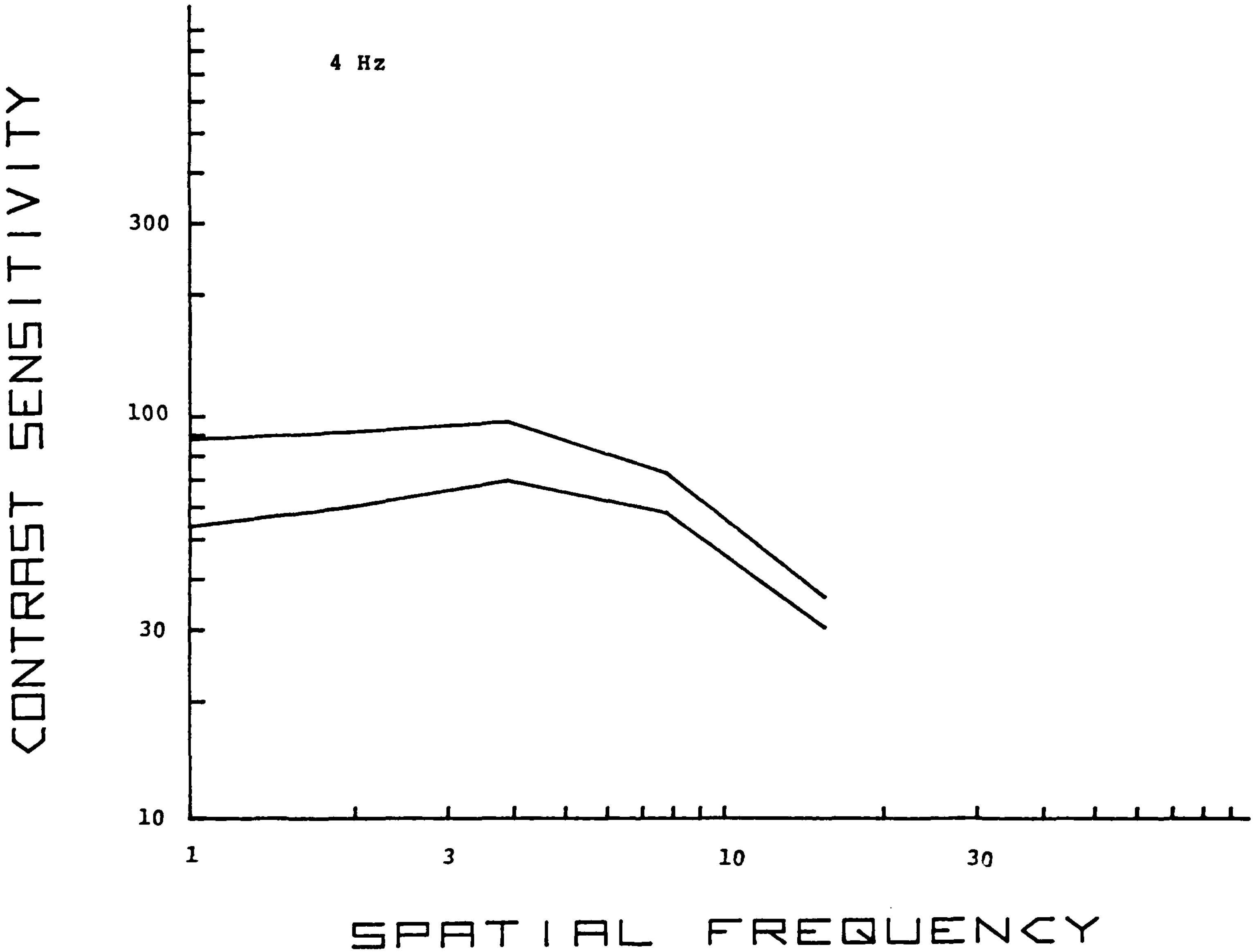
Figures 25 through 28 show detection-and-indentification-sensitivity results obtained from an observer (MM) whose results were representative of those obtained from our four observers with normal (static) CSFs. Each figure shows the detection sensitivity (upper curve) and identification sensitivity (lower curve) obtained with a given temporal frequency as a function of spatial frequency. Figures 25 through 28 show results obtained with temporal frequencies of 2 Hz, 4 Hz, 8 Hz, and 10 Hz respectively.

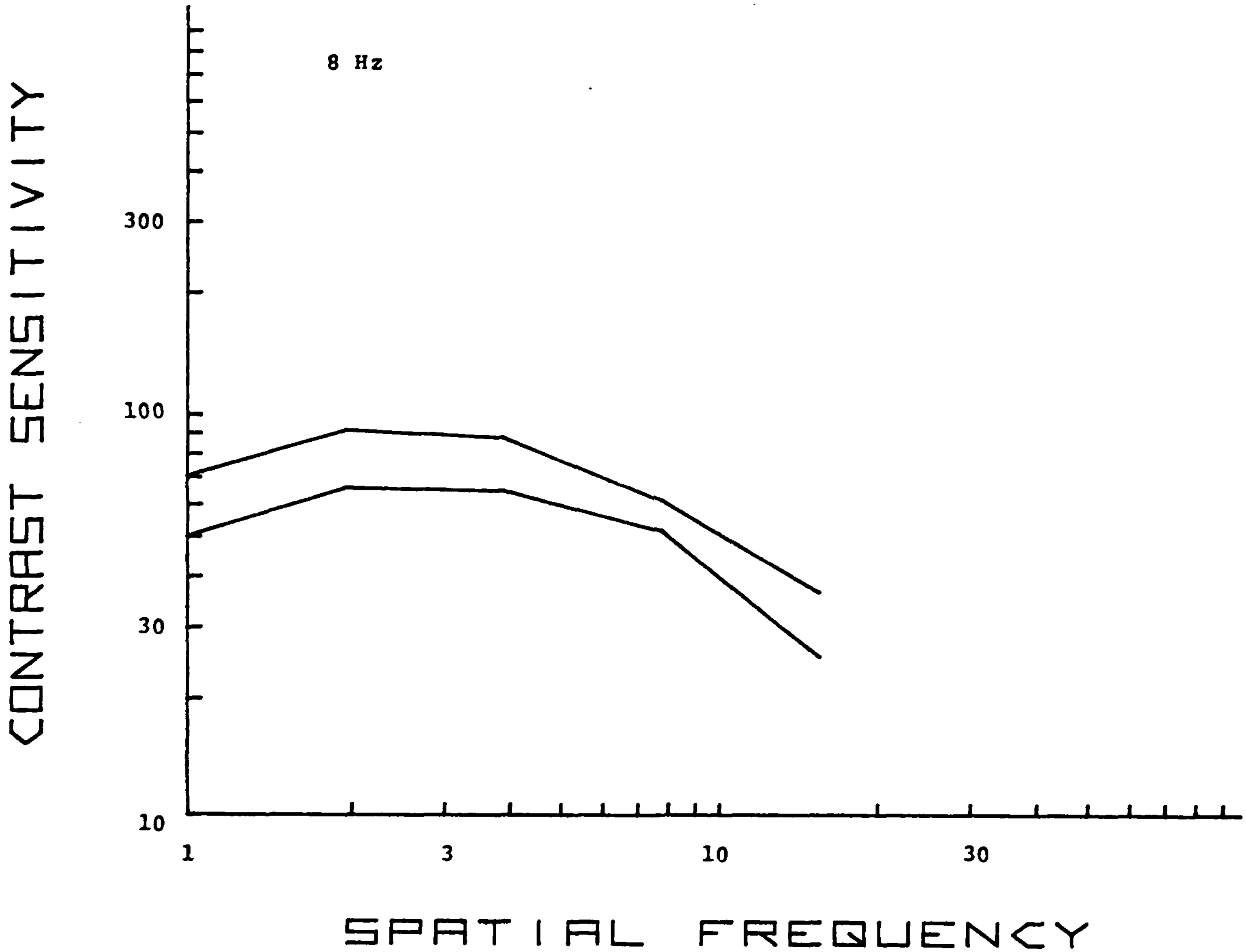
At 2 Hz, MM showed little difference between detection and identification sensitivities at spatial frequencies of 4 cycles/degree and above. This follows from our earlier observation with stationary gratings that detection and identification occurred simultaneously. Below 4 cycles/degree, however, detection, sensitivity moderately exceeds identification sensitivity. Furthermore, motion has

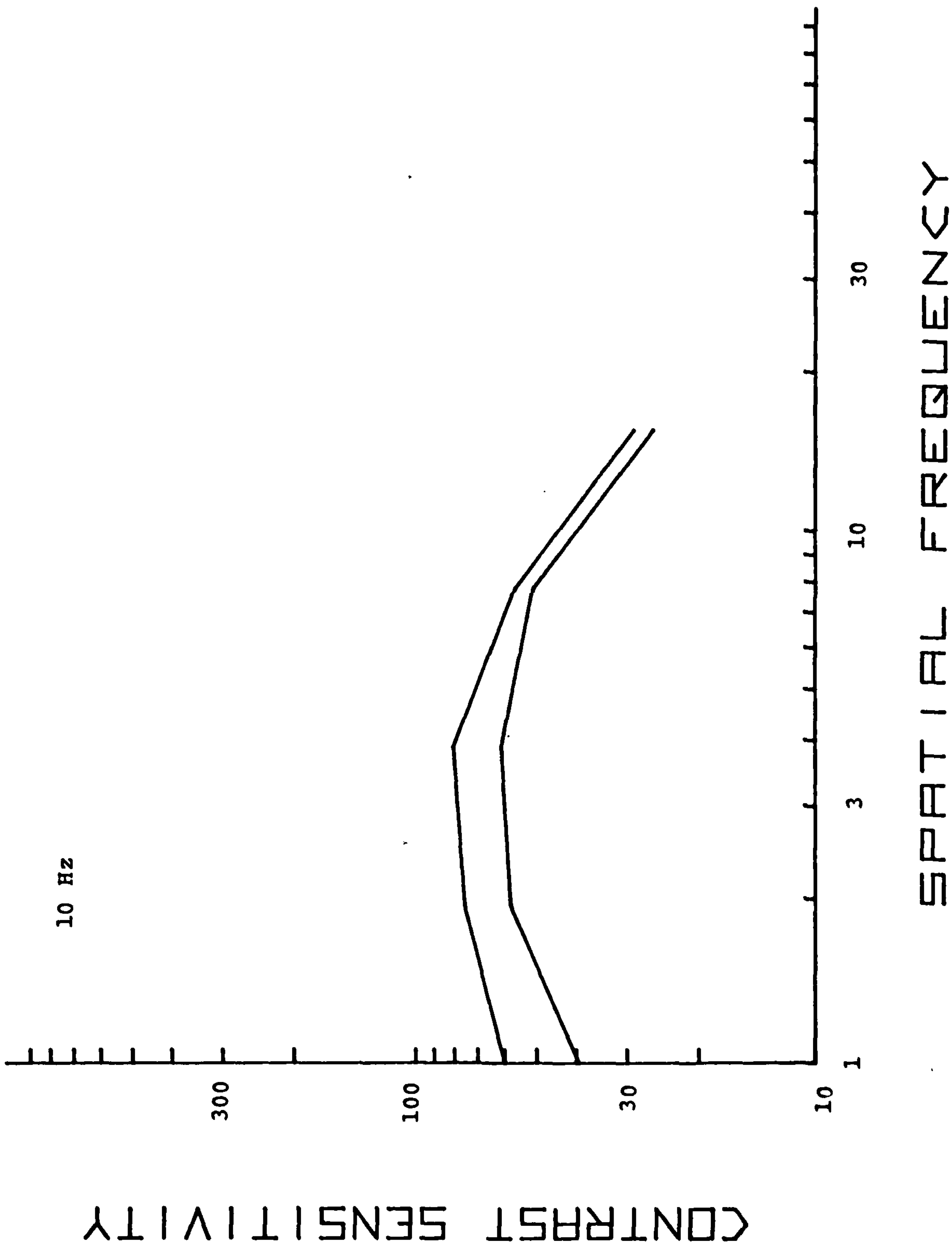
FIGURES 25-28: Detection (upper curves) and identification (lower curves) contrast sensitivities as functions of spatial frequency (in cycles/degree) for drifting sine-wave gratings. Results for observer MM only. Figure 25: Gratings drifting at a temporal rate of 2 Hz; Figure 26: temporal drift rate of 4 Hz; Figure 27: 8 Hz; Figure 28: 10 Hz.



2 Hz
1
3
10
30
SPATIAL FREQUENCY
10
30
100
300
CONTRAST SENSITIVITY


4 Hz
CONTRAST SENSITIVITY
300
100
30
10
1
3
10
30
SPATIAL FREQUENCY


8 Hz
CONTRAST SENSITIVITY
300
100
30
10
1
3
10
30
SPATIAL FREQUENCY


10 Hz
CONTRAST SENSITIVITY
10
30
100
300
SPATIAL FREQUENCY
1
3
10
30

enhanced MM's sensitivities at low spatial frequencies relative to the stimulus conditions that employed static gratings (Figure 6). That is, with motion our observers did not show a low-frequency falloff. The pattern of results shown in Figure 25 is consistent with the earlier findings of Kulikowski and Tolhurst (1973) and of Tolhurst (1973) and are also consistent with the currently popular belief that the visual system employs separate channels for the analysis of pattern and motion (cf. Sekuler, Pantle, & Levinson, 1978).

At a temporal frequency of 4 Hz (Figure 26), MM's detection sensitivity has increased to its maximum at all spatial frequencies, and she shows her greatest difference between detection and identification sensitivities at all spatial frequencies. The pattern of results shown in Figure 26 can be explained by the fact that the human motion-analyzing system is most sensitive to temporal frequencies from 3-5 Hz. Since the sensitivity of the motion-analyzing system is lowest at high spatial frequencies, the detection-and-identification-sensitivity functions converge more and more at frequencies above 8 cycles/degree. Again, these findings are consistent with the notion that the human visual system employs a motion-sensitive system (the so-called transient channel) that responds best to low spatial frequencies and intermediate temporal frequencies and that it also employs a pattern sensitive system (the sustained channel) that responds best to moderately high spatial frequencies and low temporal frequencies (cf. Pantle 1977).

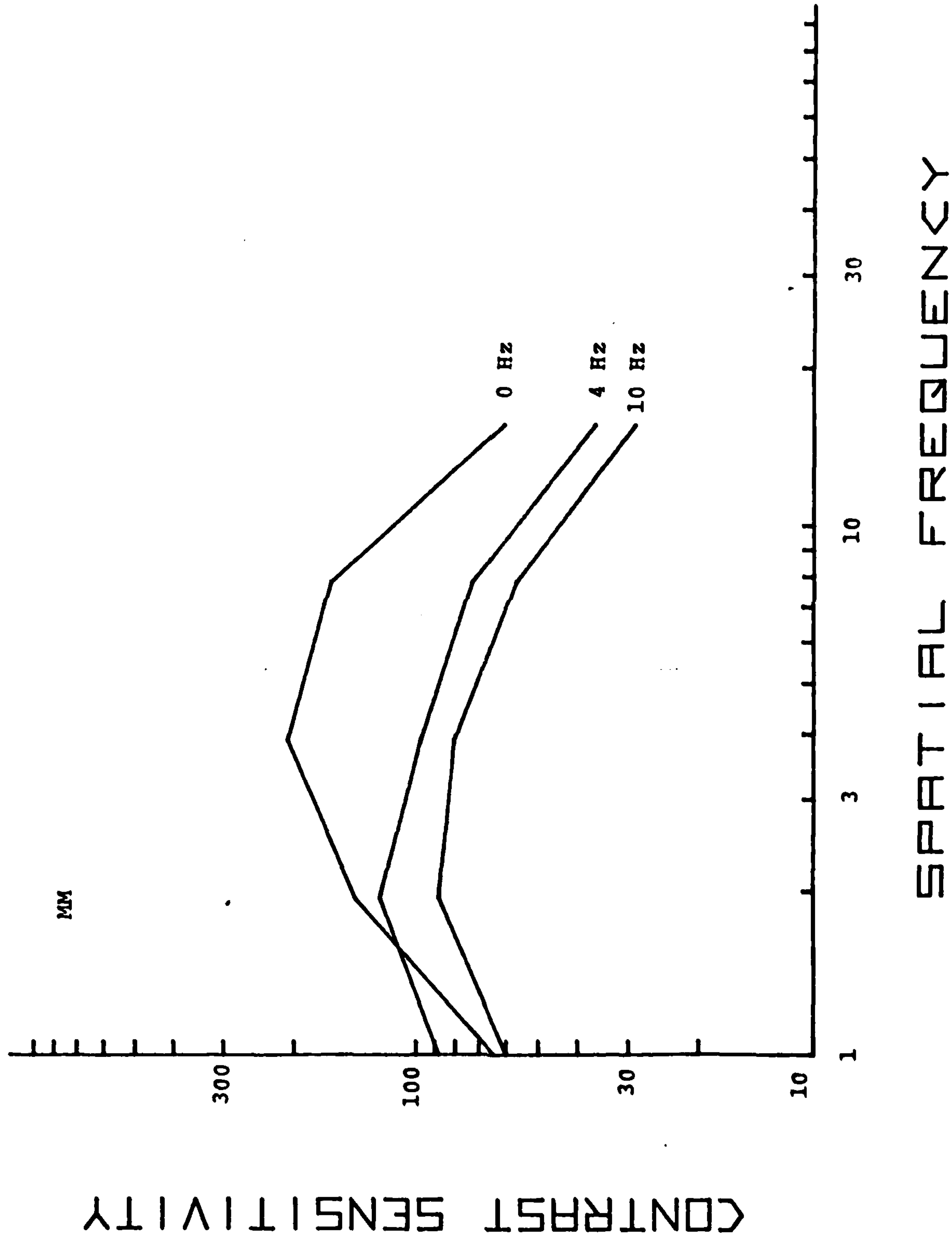
Figures 27 and 28 show MM's sensitivities at temporal

frequencies of 8 Hz and 10 Hz respectively. Sensitivity at all spatial frequencies gradually declines in these figures. By 10 Hz, the advantage to detection sensitivity at higher spatial frequencies gained by motion (cf. Figures 25 and 26) has been nearly totally lost.

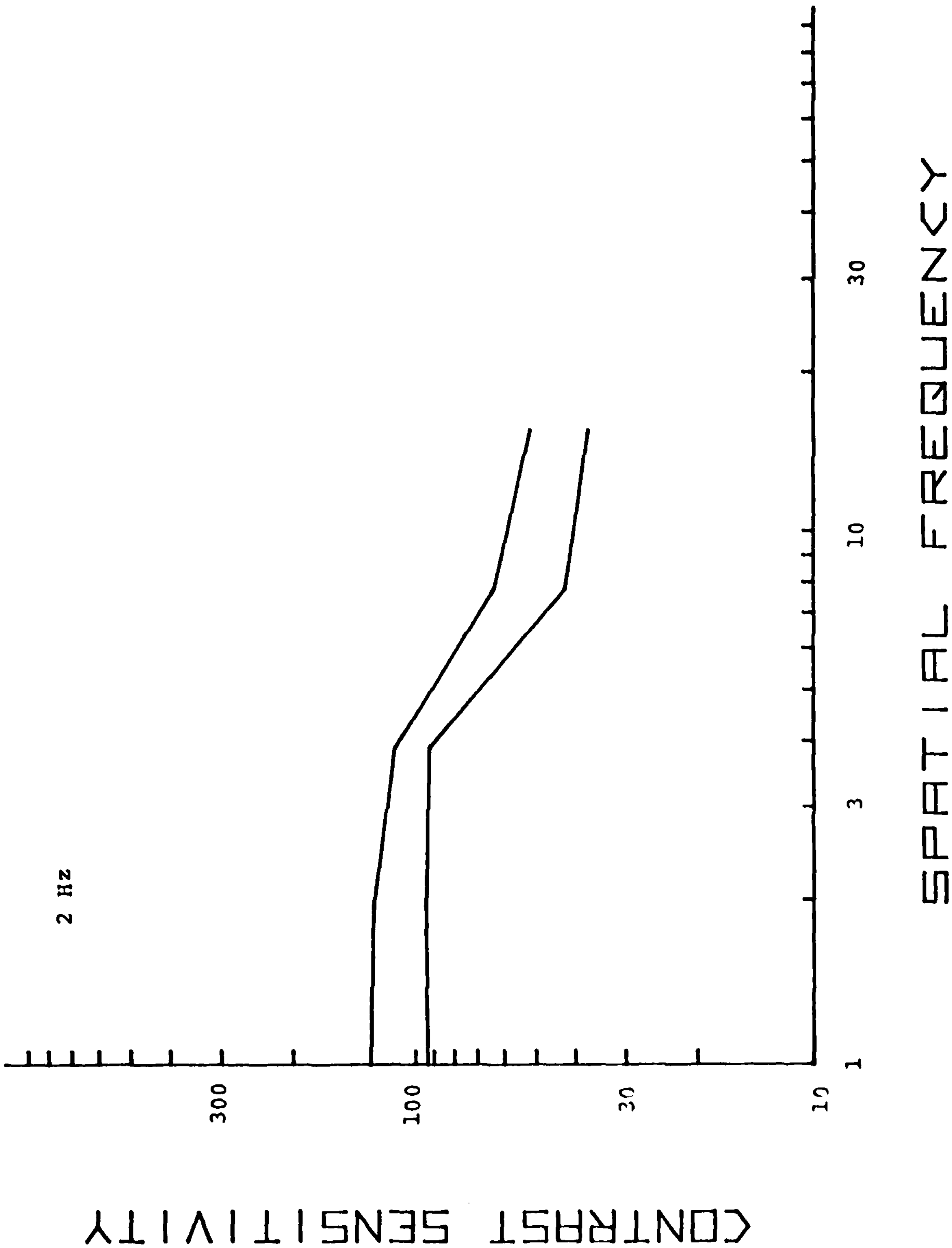
MM's results are summarized in Figure 29, which shows detection sensitivity at three temporal frequencies. The upper curve shows sensitivity for stationary gratings. With 4-Hz movement, the low spatial-frequency falloff has been attenuated. At spatial frequencies above 2 cycles/degree, motion impairs sensitivity considerably. At 10 Hz, the shape of the CSF remains the same but declines in sensitivity.

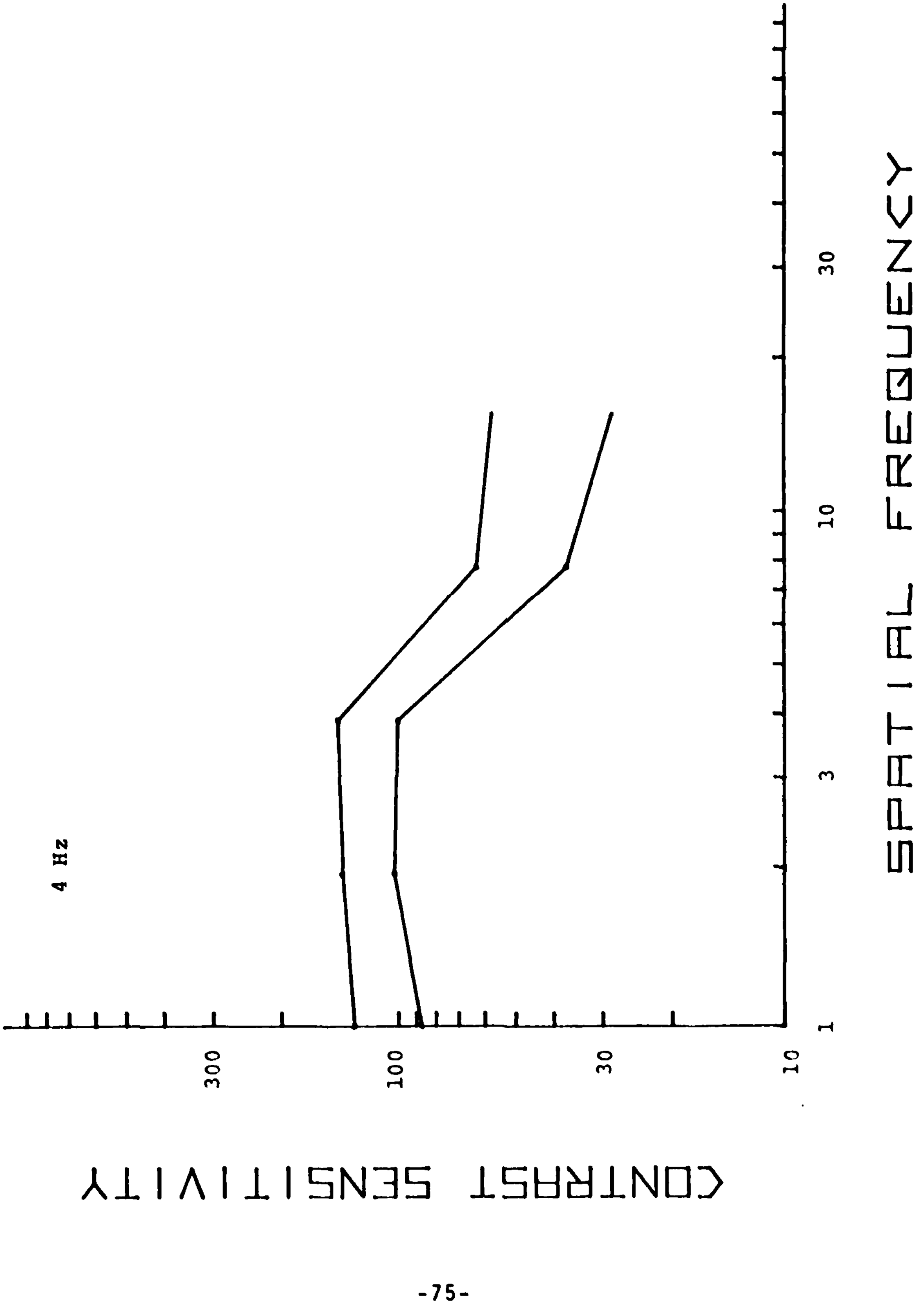
Figures 30 through 33 show the corresponding pattern of results for observer MS. MS's results are quite unusual and complex. The distinctive points are as follows: 1) MS's identification sensitivity is always considerably below his detection sensitivity. This finding is not a procedural artifact since RF yielded data under the same procedure and showed the typical similarity between detection and identification thresholds at 0 Hz and 2 Hz. 2) The difference between MS's detection and identification sensitivities grows with increasing temporal frequency. 3) MS's temporal CSFs generally do not show the typical inverted-U shape, with only the suggestion of a peak spatial frequency (2 cycles/degree) at 8 and 10 Hz. 4) MS is more sensitive to all spatial frequencies drifting at 4 Hz than he is to stationary spatial frequencies. 5) MS's ability to resolve high spatial frequencies is unaffected by stimulus movement.

FIGURE 29: Comparison of detection sensitivities obtained with stationary and drifting sine-wave gratings for observer MM. Abcissa: Spatial frequency in Cycles/degree.

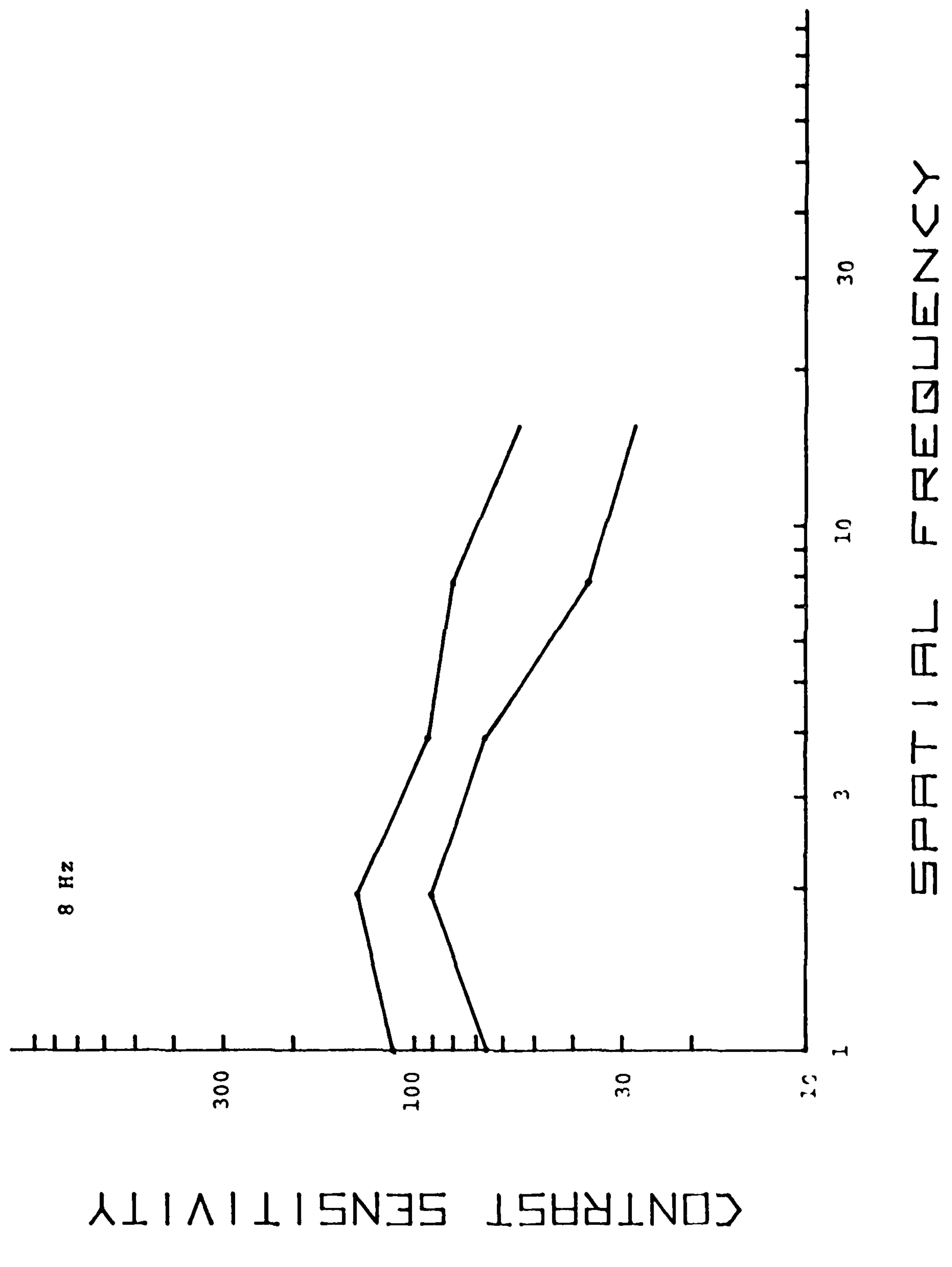

MM
0 Hz
4 Hz
10 Hz
300
100
30
10
1
3
10
30
SPATIAL FREQUENCY
CONTRAST SENSITIVITY

FIGURES 30-33: Detection (upper curves) and identification (lower curves) contrast sensitivities as functions of spatial frequency (in cycles/degree) for drifting sine-wave gratings. Results for observer MS only. Figure 30: Gratings drifting at a temporal rate of 2 Hz; Figure 31: temporal drift rate of 4 Hz; Figure 32: 8 Hz; Figure 33: 10 Hz.

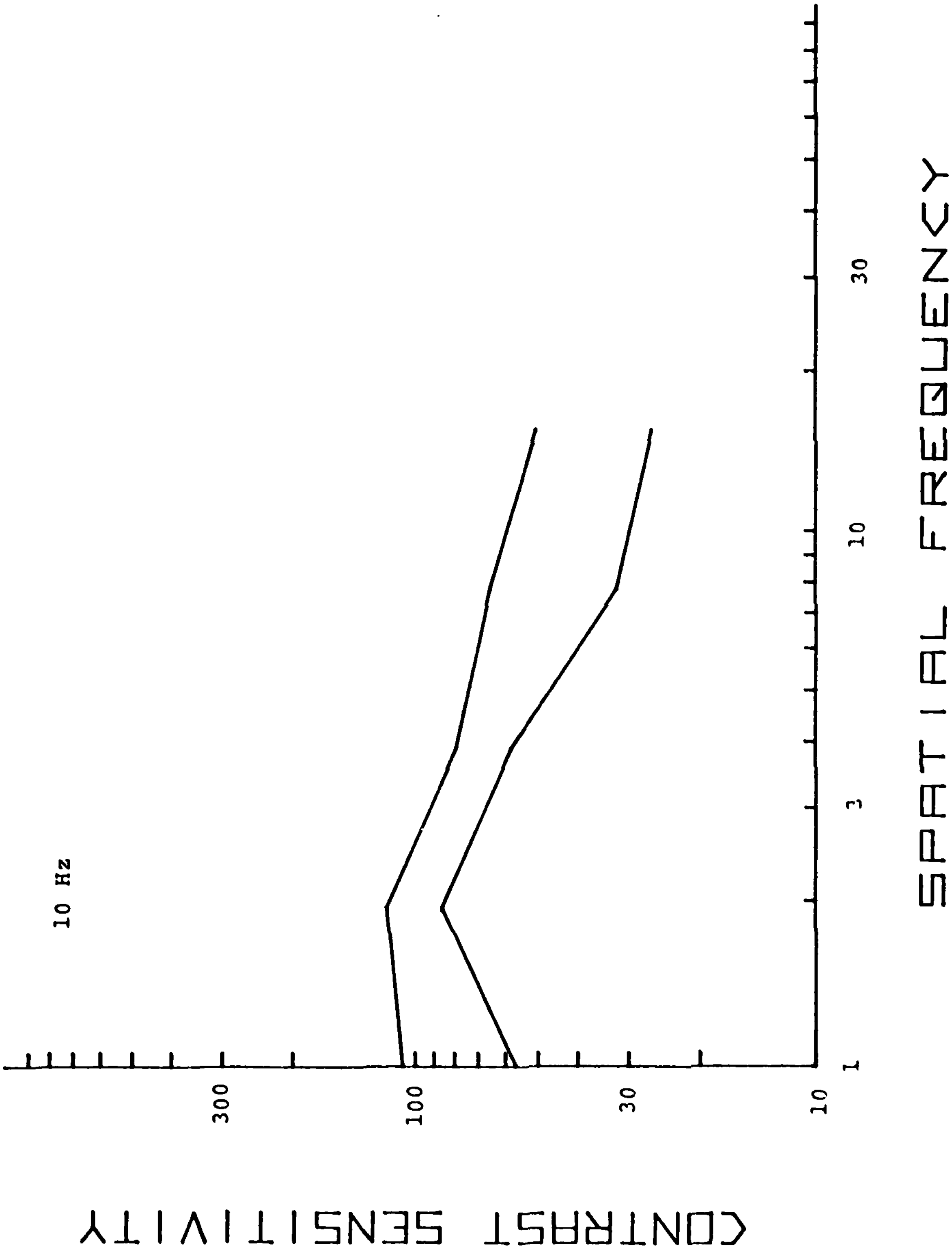

2 Hz
CONTRAST SENSITIVITY
300
100
30
10
SPATIAL FREQUENCY
1
3
10
30



4 Hz
CONTRAST SENSITIVITY
300
100
30
10
1
3
10
30
SPATIAL FREQUENCY



8 Hz
CONTRAST SENSITIVITY
300
100
30
SPATIAL FREQUENCY
1
3
10
30


10 Hz
CONTRAST SENSITIVITY
10
30
100
300
SPATIAL FREQUENCY
1
3
10
30

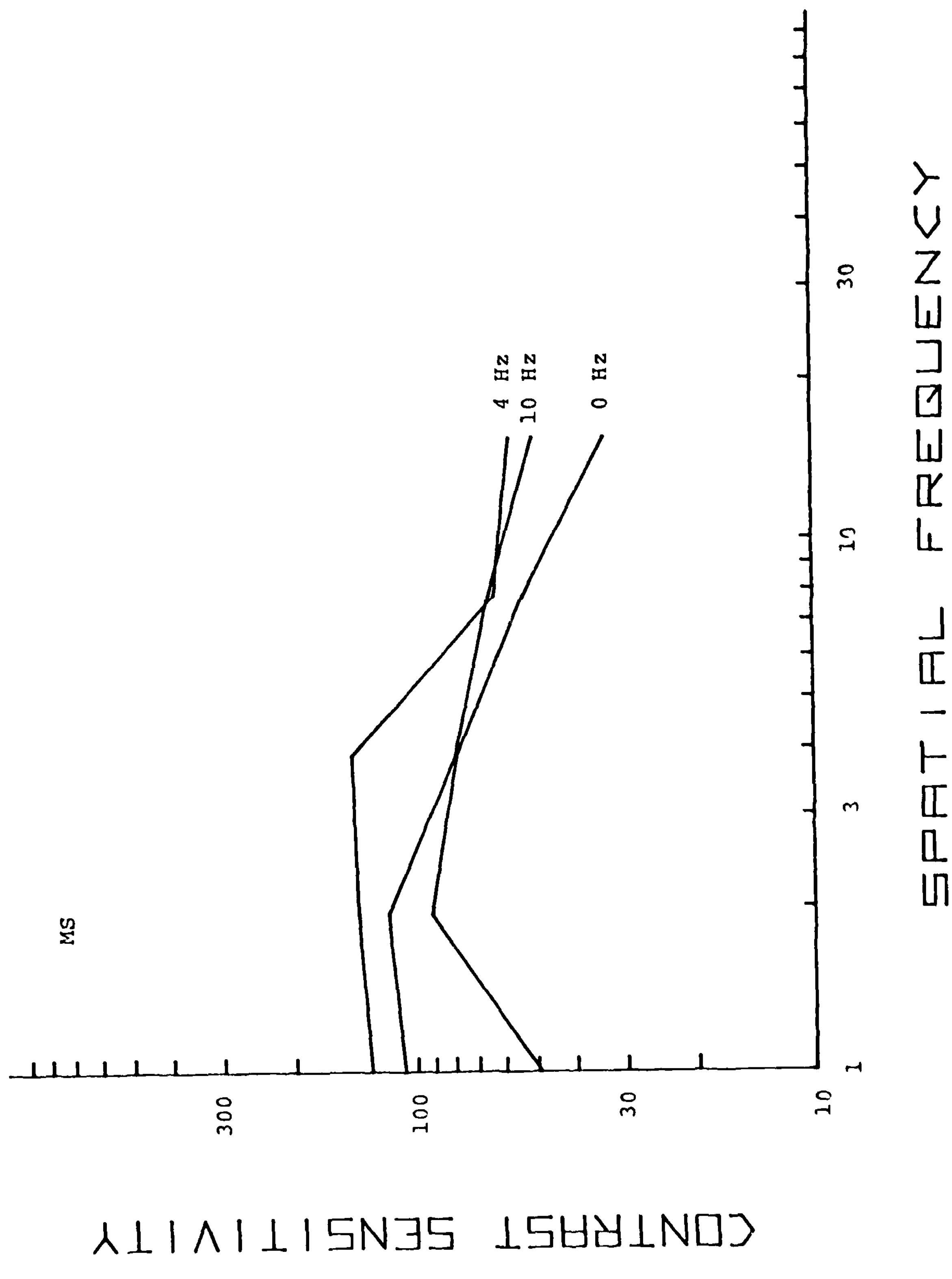
MS's results are summarized in Figure 34 which shows the detection sensitivity, for each of three temporal frequencies, 0 Hz, 4 Hz, and 10 Hz. MS is clearly most sensitive at 4 Hz, which indicates a relatively normal transient system. In fact, the 4 Hz temporal drift rate enhanced MS's low spatial frequency sensitivity more than for observer MM or MB. By 10 Hz, MS's sensitivity has dropped below his sensitivity to stationary gratings for spatial frequencies below about 4 cycles/degree.

MS's results suggest that he has an unimpaired transient (i.e., motion-sensitive) system and an impaired sustained (i.e., high spatial frequency or pattern-sensitive) system. If detection of moving Snellen-letter stimuli relies heavily on transient mechanisms, we would expect MS's detection CSFs to be comparatively normal. If sustained mechanisms are wholly or mainly involved in identification we would expect to see a deviation in MS's identification CSFs and that such a deviation might be size-dependent. Furthermore, for the group as a whole we expect to see the detection-to-identification threshold contrast ratio change as a function of temporal frequency. This should be true because sustained and transient mechanicsms are differentially tuned to temporal (and spatial) frequency and because their relative involvement should vary with temporal frequency and the size of Snellen-letter stimuli.

B. Results obtained with drifting Snellen-letter stimuli.

In three separate experiments we examined the effect of

FIGURE 34: Comparison of detection sensitivities obtained with stationary and drifting sine-wave gratings for observer MS. Abcissa: Spatial frequency in cycles/degree.

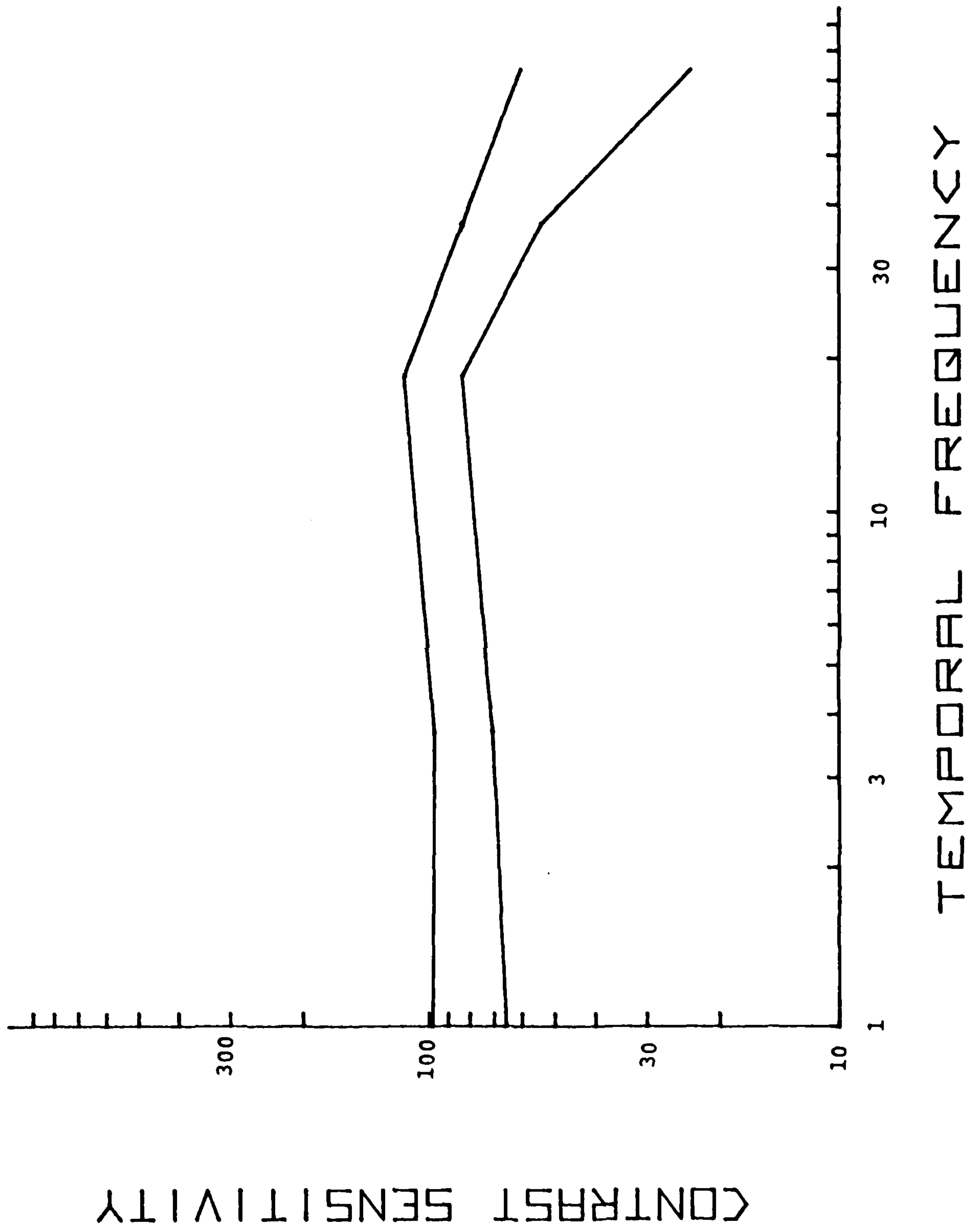

MS
4 Hz
10 Hz
0 Hz
300
100
30
10
1
3
10
30
CONTRAST SENSITIVITY
SPATIAL FREQUENCY

stimulus motion on detection and identification contrast sensitivity. Once again, we also varied the size and rotation of the Snellen letters. To produce our stimulus movement, we oscillated the mirror in our system at a given temporal rate, 0 Hz, .04 Hz, .2 Hz, .4 Hz, or .8 Hz. The corresponding stimulus velocities were 0 degrees/second, 1.67 degrees/second, 8.3 degrees/second, 16.61 degrees/second, and 33.22 degrees/second. The temporal frequencies of any display depended upon both the fundamental spatial frequency of the stimulus letter and its velocity. The temporal frequencies of the stimuli are shown in the figures discussed below.

1. Effects of motion and size (spatial frequency).

For the group of observers in general, Figure 35 shows the effect of temporal frequency on detection and identification sensitivity for letters of a single fundamental spatial frequency, 2.28 cycles/degree, and rotated to 0°. For convenience, data obtained at 0 Hz are plotted on the ordinate in this and in successive figures.) Standard deviations were once again in the neighborhood of 9%. Contrary to our expectations, temporal frequency (or velocity) had little effect on sensitivity for temporal frequencies at and below 20 Hz. Beyond 20 Hz, both detection and identification sensitivities decline with increasing temporal frequency, although the rate of decline is greater for identification sensitivity than for detection sensitivity. The lack of effect of temporal frequency below 20 Hz (a velocity of about 8.3 degrees/second) is not

FIGURE 35: Detection (upper curve) and identification (lower curve) contrast sensitivities as functions of the temporal frequency (in Hz) of drifting Snellen-letter stimuli (2.28 cycles/degree). Data points are averaged over observers and the various letter stimuli.


CONTRAST SENSITIVITY
300
100
30
10
1
3
10
30
TEMPORAL FREQUENCY

without explanation. First, motion tends to attenuate the low-frequency falloff in the spatial CSF. Thus, for example, at 2.28 cycles/degree MB's spatial CSF for detection changes by only a factor of .29; for MM, .22. Second, and perhaps more importantly, the human visual system is thought to contain elements selective to narrow ranges of temporal frequency (cf. Pantle, 1978; Sekuler, Pantle, & Levinson, 1978). Generally, studies that have investigated temporal-frequency channels in human vision have employed physically simple stimuli like moving sine-wave gratings or whole-field flicker (e.g., Pantle 1971, 1978; Nilsson, et al., 1974). On the other hand, researchers studying the existence of velocity-sensitive elements in human vision have tended to use complex stimuli like moving dots, bars, or square-wave gratings (e.g., Ganz & Lange, 1973; Grüsser & Grüsser-Cornehls, 1973; Hubel & Wiesel, 1965; Movshon, 1974; Pantle & Sekuler, 1968; Pettigrew et al., 1968). Since the stimulus tends to select for particular selective processes in psychophysical studies, and since our Snellen-letter stimuli are complex, it is possible that we have tapped the population of velocity-sensitive elements in human vision. If, at their peak response, different sub-populations of velocity-sensitive elements are equally sensitive, we would expect to find relatively flat functions like those shown in Figure 35. In fact, in a velocity-discrimination task with two drifting gratings (arguably a complex stimulus), Pantle (1978) obtained a temporal-frequency sensitivity function not unlike the one

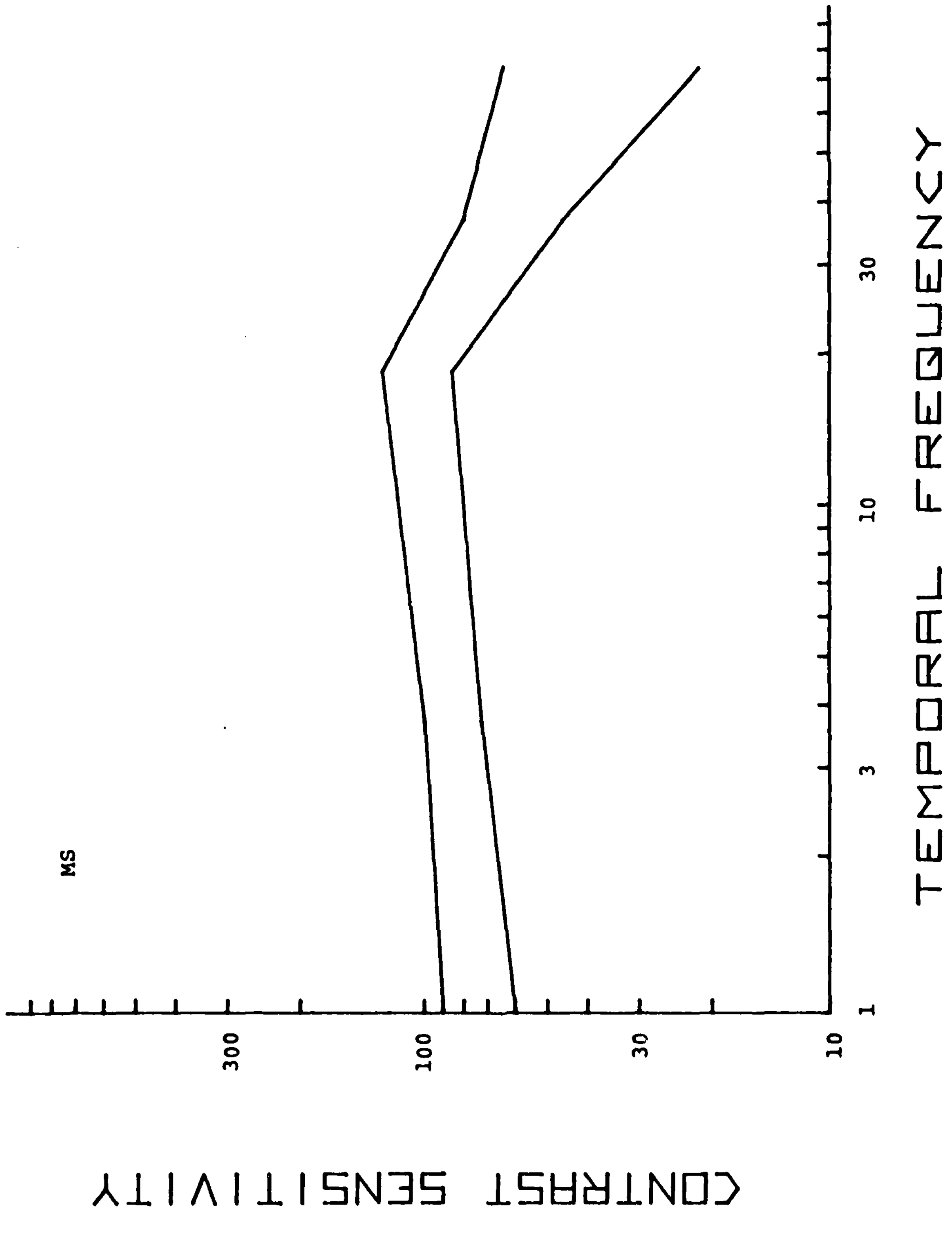
we present in Figure 35 and attributed its shape to the response of directionally selective motion channels.

With temporal frequency, as with spatial frequency, we found in Figure 35 that the ratio of detection-threshold contrast to identification-threshold contrast was relatively constant (≈ .73) up to a high-frequency cutoff (in this case, 20 Hz). At the next two highest frequencies, the ratio was .64 and .39 respectively. This result is consistent with the findings of Petersik (1980).

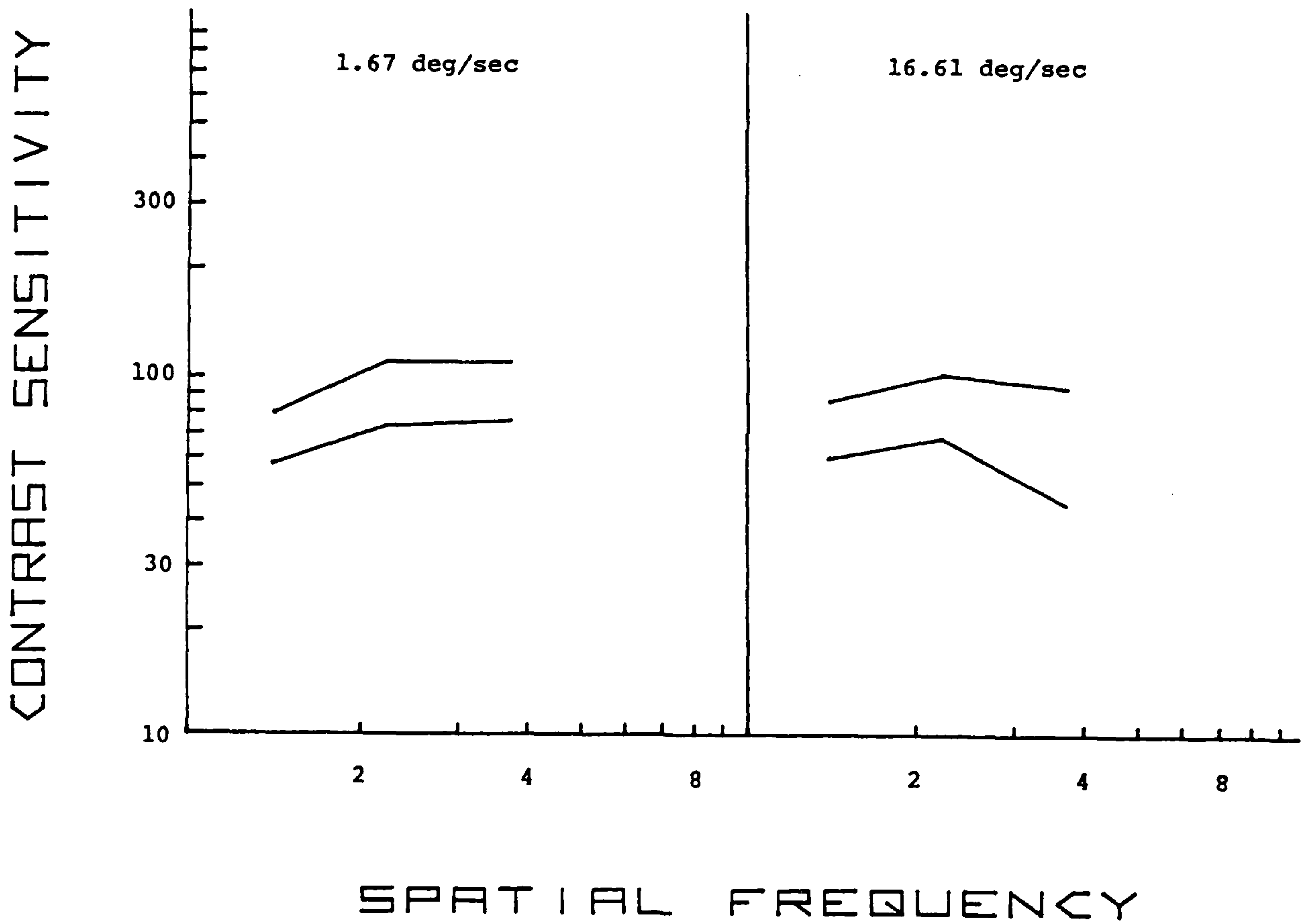
Figure 36 shows the effect of temporal frequency (or velocity) on observer MS's detection and identification sensitivities. As can be seen, MS deviated very little from the group functions shown in Figure 35. This is consistent with our belief that MS has essentially normal transient, or motion-sensitive, channels.

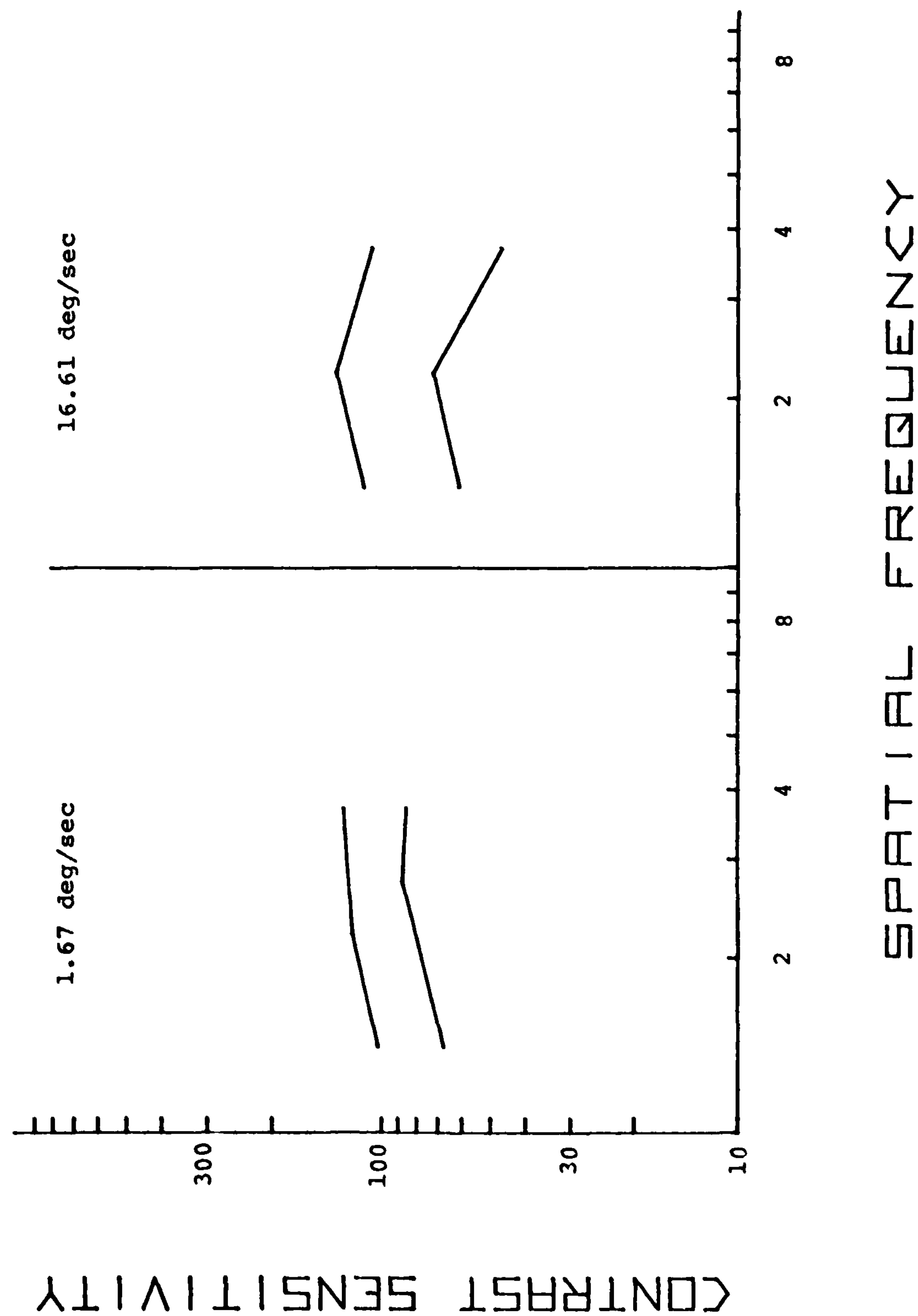
In one experiment we examined the joint effects of fundamental spatial frequency (1.43, 2.28, or 3.81 cycles/degree) and velocity (1.67 or 16.61 degrees/second) on detection and identification sensitivity. In each case, the test letters were rotated to 0°. Figure 37 shows the results of this experiment for the group. The curves in the lefthand panel are the detection (upper) and identification (lower) functions for stimuli moving at 1.67 degrees/second. The curves in the righthand panel show corresponding information for letters moving at 16.61 degrees/second. The temporal frequencies represented by the data points in the lefthand panel are, from left to

FIGURE 36: Same as Figure 35; data for observer MS only.


MS
1
3
10
30
TEMPORAL FREQUENCY
10
30
100
300
CONTRAST SENSITIVITY

FIGURES 37-38: Detection (upper curves) and identification (lower curves) constrast sensitivity in response to Snellen-letter stimuli drifting at either 1.67 degrees/second (left panel) or 16.61 degrees/second (right panel) as functions of the fundamental spatial frequencies (in cycles/degree) of the stimuli. Figure 37: Data averaged over observers and Snellen letters. Figure 38: Data for observer MS, averaged over Snellen letters.


1.67 deg/sec
16.61 deg/sec
CONTRAST SENSITIVITY
300
100
30
10
2
4
8
2
4
8
SPATIAL FREQUENCY


1.67 deg/sec
16.61 deg/sec
CONTRAST SENSITIVITY
300
100
30
10
2
4
8
2
4
8
SPATIAL FREQUENCY

right, 2.39, 3.81, and 6.36 Hz; in the righthand panel, 23.75, 37.87, and 63.28 Hz. Assuming the operation of velocity-selective elements, the data in Figure 37 suggests an interaction between spatial frequency and velocity with regard to identification sensitivity. At 1.67 degrees/second, identification sensitivity does not decline over this range of spatial frequencies. On the other hand, at 16.61 degrees/second, a decline in sensitivity is apparent at the highest spatial frequency. This loss of sensitivity could be the result of the normal decline in observers' temporal CSFs at high temporal frequencies. In this case a relatively high spatial frequency was moved at a high velocity, resulting in a correspondingly high temporal frequency. Detection sensitivity does not appear to be influenced by velocity. These findings are again consistent with the concept of sustained and transient channels in human vision. Transient channels, which respond well to movement, may be responsible for detection and uninfluenced by changes in velocity. On the other hand, sustained channels do not respond well to movement particularly when high spatial and high temporal frequencies are involved. If sustained channels are relatively more responsible for identification than transient channels, this could also account for the relatively steep decline in identification sensitivity at the highest spatial frequency and velocity we used.

Another aspect of the data apparent in Figure 37 was that the functions have lost the low spatial frequency

falloffs apparent in the curves for 0°-rotation stationary letters (Figure 11). This finding is consistent with the CSFs obtained with moving sine-wave gratings. At low spatial frequencies, movement enhanced both detection and identification sensitivities relative to the stationary conditions.

We had predicted that detection-to-identification threshold contrast bandwidths would change as a function of stimulus movement. Unfortunately, because of the limited range of spatial frequencies we were able to use in this experiment, it was impossible to estimate the bandwidth in the 1.67 degrees/second condition. However, in the 16.61 degrees/second condition, our estimate of the bandwidth (obtained as in section III.B.2) was 2.88. Recall that for 0°-rotation stationary Snellen letters the bandwidth estimate was 1.10. Therefore, we can conclude that motion over the range of velocities we have studied increases the range of spatial frequencies used for detection and identification. This increase in bandwidth appears to be accompanied by a relative increase in both detection and identification sensitivities at low fundamental spatial frequencies and an overall depression of identification sensitivity (compared to stationary conditions) that is accelerated at higher spatial frequencies.

The results of MS in this experiment were as expected: MS showed the beginning of a decline in identification

sensitivity at a relatively low spatial frequency of 3.81 cycles/degree with the slowest stimulus velocity. With the higher velocity, MS's identification sensitivity was depressed over the range of spatial frequencies (Figure 38). We also calculated the estimate of the detection-to-identification contrast threshold bandwidth for observer MS in the 16.61 degrees/second condition. This estimate was 4.0 and represents an increase by a factor of 3.05 over the estimate produced with stationary stimuli (1.31). This estimate is also the largest produced by any of our subjects under any conditions and probably is due to MS's lack of sensitivity in sustained-like channels coupled with stimulus conditions (i.e., movement) that favor transient-like channels.

The results of this experiment are summarized in a somewhat different manner in Figures 39 and 40 where we compare the group's sensitivity to moving Snellen letters to the group's sensitivity to stationary Snellen letters of various fundamental spatial frequencies. Figure 39 shows the results for stimuli moving at 1.67 degrees/second (and stationary stimuli); Figure 40, 16.61 degrees/second. In each figure, detection sensitivities are shown in the lefthand panel and identification sensitivities in the righthand panel. Sensitivities for moving stimuli are represented by the shorter curves for stimuli from 1.43 to 3.81 cycles/degree.

The data in Figure 39 for 1.67 degrees/second reveal that movement enhanced detection sensitiviity relative to

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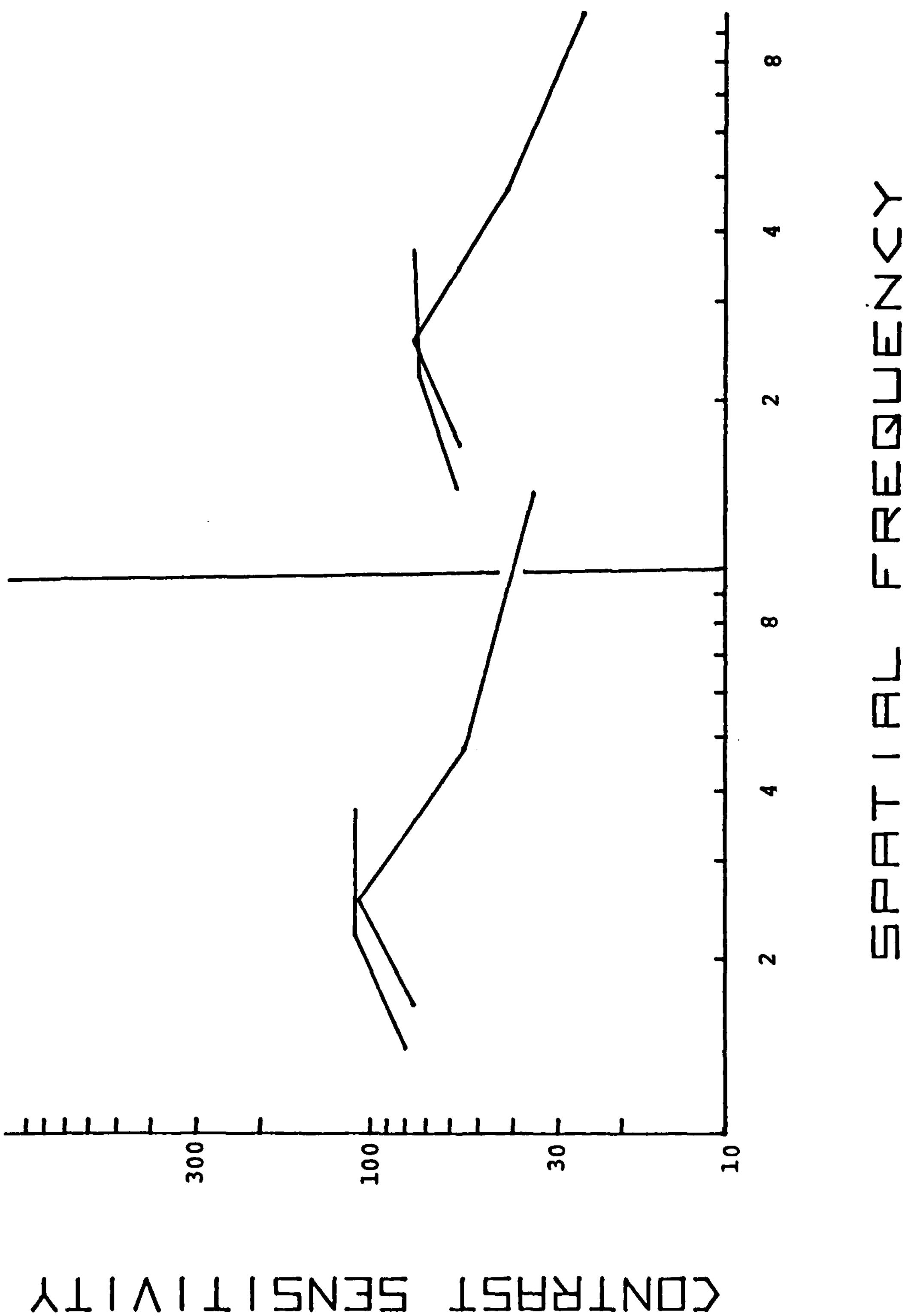
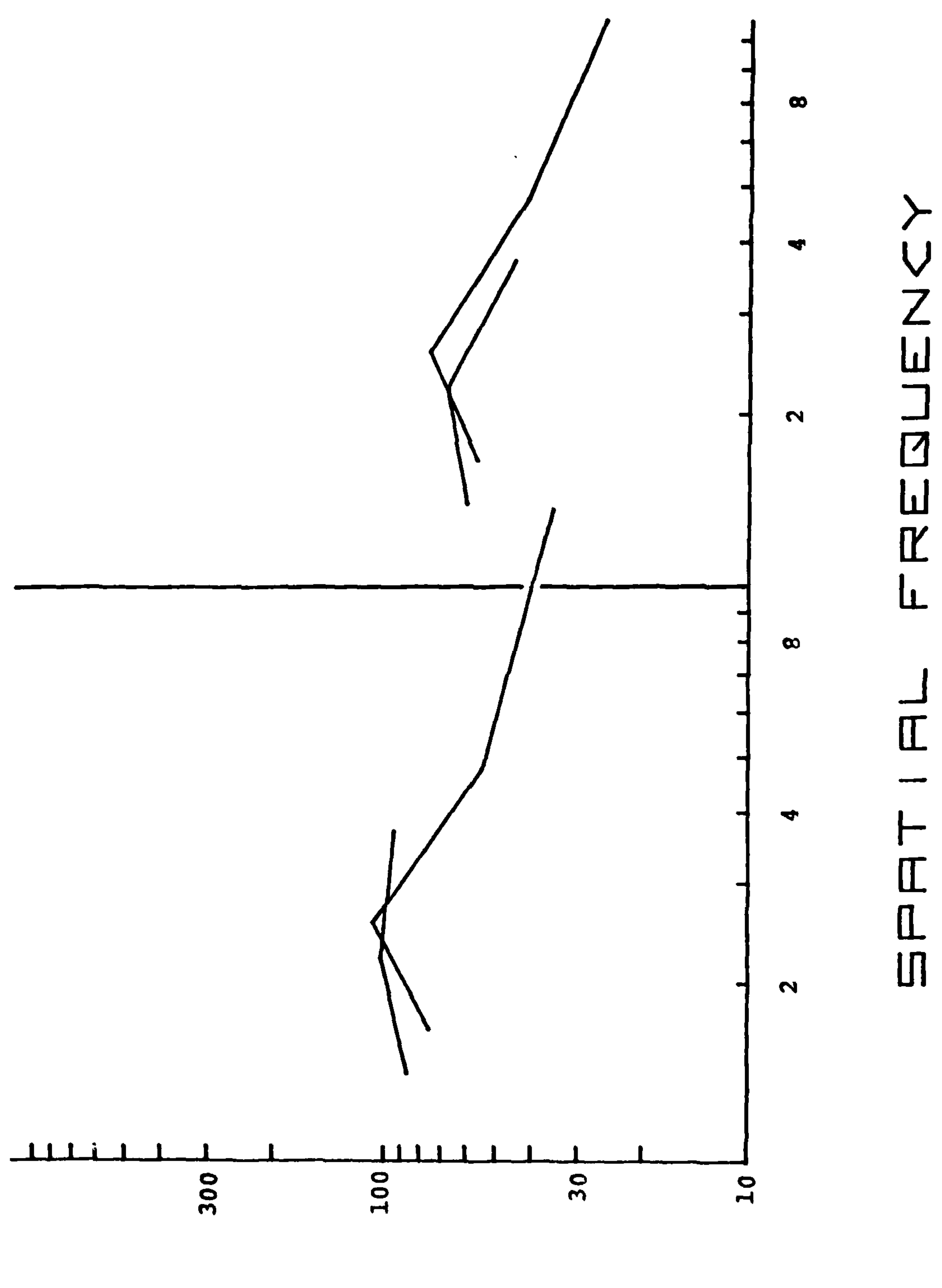
stationary conditions. While the effect was not quite as great, movement also elevated identification sensitivity relative to stationary conditions. For each type of sensitivity, movement at 1.67 degrees/second prevented the high-frequency falloff that occurred for stationary letters above about 2.4 cycles/degree. These results are probably due to the relative increase in sensitivity to low-to-intermediate spatial frequencies that occurs in response to relatively low temporal frequencies. Motion at 1.67 degrees/second also attenuated the low spatial-frequency falloff for both the detection and identification of Snellen-letter stimuli. In comparison, the data in Figure 40 for 16.61 degrees/second show a somewhat different pattern of results. For detection sensitivity, the function obtained with moving stimuli remains elevated at the lowest spatial frequency, but is somewhat depressed at the two highest spatial frequencies relative to the 1.67-cycles/degree condition. On the other hand, detection sensitivity for stimuli moving at 16.61 degrees/second does not show a high-frequency falloff and remains generally greater than the corresponding sensitivity to stationary letters. However, identification sensitivity to 16.61 degrees/second moving letters is depressed enough to be at or below the corresponding sensitivity to stationary letters at the two higher fundamental spatial frequencies. Furthermore, a high-frequency falloff relative to identification sensitivity at 1.67 degrees/second is quite evident in the 16.61-degrees/second function.

FIGURES 39-40: Detection (lefthand panels) and identification (righthand panels) contrast sensitivities in response to both moving (short, upper curves) and stationary (long, lower curves) as functions of spatial frequency (in cycles/degree). Data points are averaged over observers and Snellen-letter stimuli. Figure 39: Stimuli drifting at 1.67 degree/second and stationary; Figure 40: Stimuli drifting at 16.61 degrees/second and stationary.


CONTRAST SENSITIVITY
300
100
30
10
2
4
8
2
4
8
SPATIAL FREQUENCY

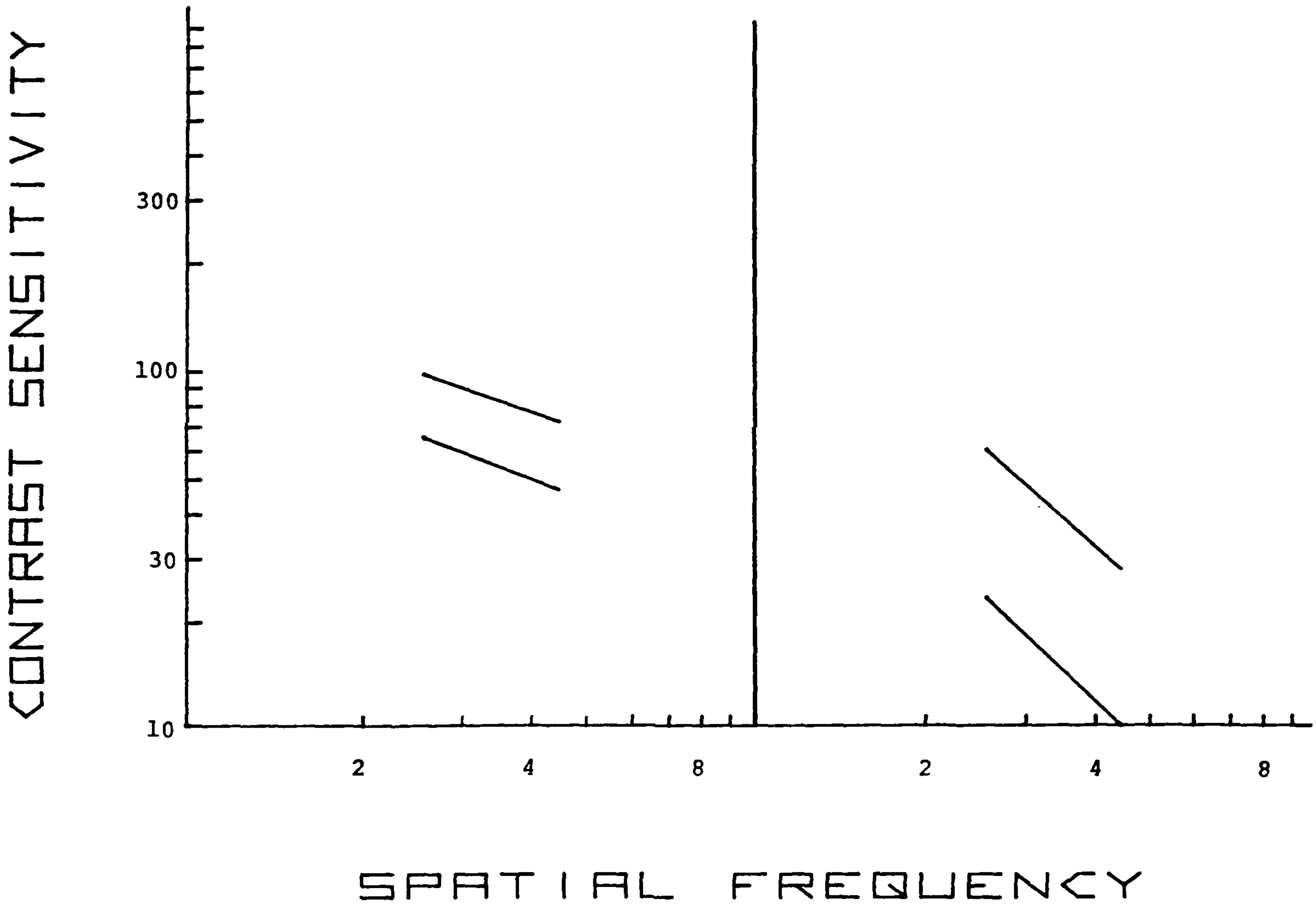

CONTRAST SENSITIVITY
300
100
30
10
2
4
8
2
4
8
SPATIAL FREQUENCY

These findings agree well with Ginsburg's suggestion that identification relies on a range of spatial frequencies that is higher than those used for detection: Movement at any velocity within the range of movement-sensitivity in human vision enhances detection of letters at low spatial frequencies, probably because of the increased sensitivity of transient channels; movement at velocities and spatial frequencies great enough to yield intermediate-to-high temporal frequencies attenuates identification sensitivity, probably because of the decrease of sensitivity in sustained channels.

2. Effects of motion and rotation

In order to examine the joint effects of rotation and movement, and to study a higher stimulus velocity (33.2 degrees/second), we collected detection and identification contrast thresholds with Snellen-letter stimuli rotated at either 0° or 75° (which also changed fundamental spatial frequency from 2.28 to 4.57 cycles/degree). Figure 41 shows the results of this experiment, with data from the stationary condition in the lefthand panel and data from the 33.2-degrees/second condition in the righthand panel. Data in the stationary condition are in good agreement with the results of our earlier experiments. The new, higher stimulus velocity increased the rate of decline in both detection and identification sensitivity as a function of rotation (spatial frequency). Furthermore, identification sensitivity was depressed further below detec-

FIGURE 41: Detection (upper functions) and identification (lower functions) contrast sensitivities in response to stationary (lefthand panel) stimuli and stimuli drifting at 33.2 degrees/second (righthand panel) as functions of the fundamental spatial frequency (in cycles/degree) of Snellen-letter stimuli rotated to 0° (lefthand points in each function) and 75° (righthand points in each function). Data are averaged over observers and Snellen-letter stimuli.


CONTRAST SENSITIVITY
300
100
30
10
2
4
8
2
4
8
SPATIAL FREQUENCY

tion sensitivity than in the stationary conditions. This finding is in good agreement with the conclusions drawn thus far: If identification requires higher spatial frequencies than detection, and if identification relies more on sustained mechanisms than does detection, we expect to see identification sensitivity decline rapidly relative to detection as stimulus velocity increases (i.e., as the temporal frequencies corresponding to the spatial frequencies required for identification increase).

## V. ADDITIONAL EXPERIMENTS

The results obtained thus far suggested additional observations that could potentially reveal more about the nature of the perceptual mechanisms underlying detection and identification judgments. In the first of two additional experiments we collected detection and identification contrast thresholds under conditions in which the stimulus itself flickered at various temporal frequencies. In the second experiment, subjects adapted to each of several spatial frequencies and subsequently adjusted identification thresholds for Snellen letters of various sizes.

### A. Contrast sensitivity in response to flickering stimuli

Because a flickering stimulus lacks the single predominant directional vector that a moving stimulus has, many researchers prefer to use flicker in the study of the temporal properties of the human visual system (cf. Kelley, 1972). In order to study the effects of temporal variation in the absence of a single direction of movement on detection and identification contrast thresholds, we devised a method of flickering the Snellen-letter stimulus without greatly altering the average luminance of the display.

#### 1. Methods of Procedure

The general apparatus has been described at the beginning of this report. In this experiment, the scanner-and-mirror assembly was not driven by the function generator so that the stimulus letter did not move. However, the

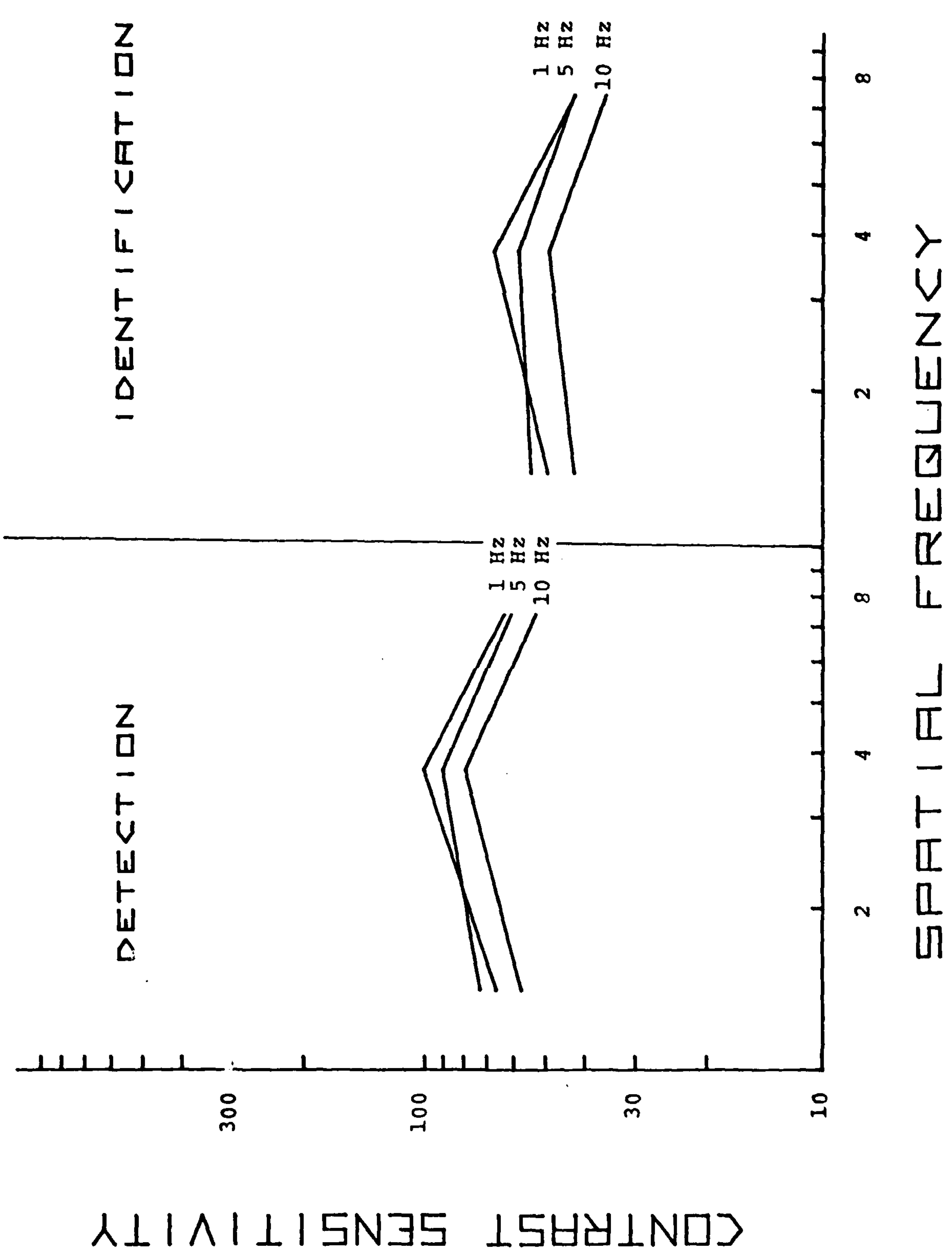
shutter in front of the stimulus projector ($p_2$ in Figure 5) was driven by a square-wave signal from the function generator, creating flicker in the stimulus channel. Since the luminance of the stimulus channel is low (relative to the "blank" channel, $p_1$ in Figure 5) when the subject is at contrast threshold, there was little detectable whole-field flicker in these experiments.

There were 24 experimental conditions in this experiment, resulting from the factorial combination of two types of contrast threshold (detection and identification), four flicker rates (1.0, 2.5, 5.0, and 10 Hz), and three fundamental spatial frequencies of the Snellen-letter stimuli (1.43, 3.81, and 7.61 cycles/degree). In this experiment, only the letters E and L were used as test stimuli. One experimental session consisted of a block of stimulus presentations in which flicker rate and spatial frequency were randomized. Once again, observers MM and MB collected detection and identification thresholds separately, whereas MS and RF found an identification threshold after each detection threshold. TP was not an observer in this experiment. Luminance was 20 cd/$m^2$.

2. Results and discussion

Figure 42 shows the effects of three flicker rates on the detection (lefthand panel) and identification (righthand panel) sensitivities of our group of observers. At the lowest fundamental spatial frequency (1.43 cycles/degree) the stimuli flickered at 5 Hz always yield the highest sensitivities, irrespective of the criterion.

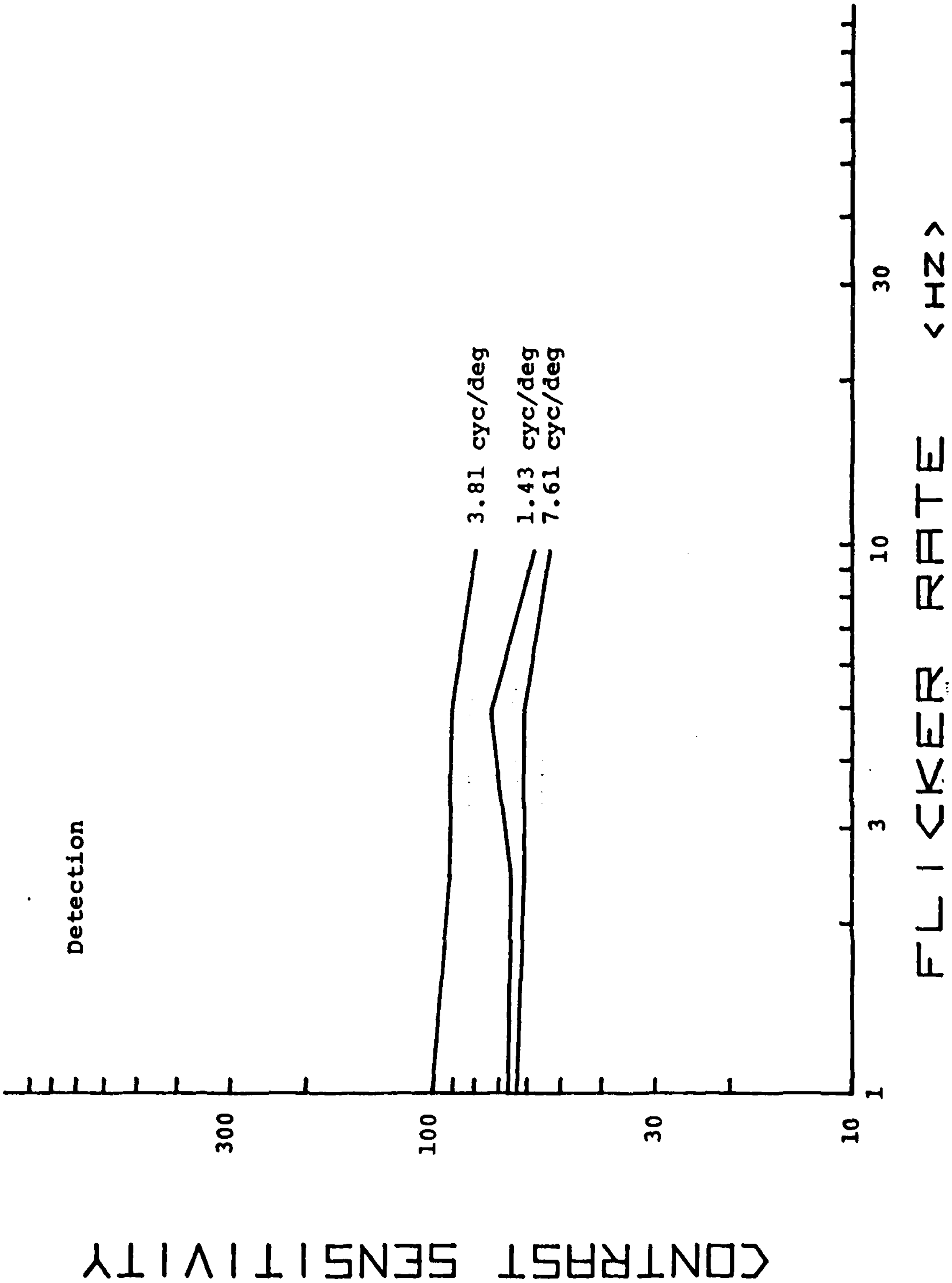
FIGURE 42: Detection and identification contrast sensitivities of the group of four observers as functions of the spatial frequency (in cycles/degree) of Snellen-letter targets flickered at various frequencies (separate functions in each panel). Data points are averaged over Snellen-letter stimuli.


DETECTION
IDENTIFICATION
1 Hz
5 Hz
10 Hz
1 Hz
5 Hz
10 Hz
2
4
8
2
4
8
SPATIAL FREQUENCY
10
30
100
300
CONTRAST SENSITIVITY

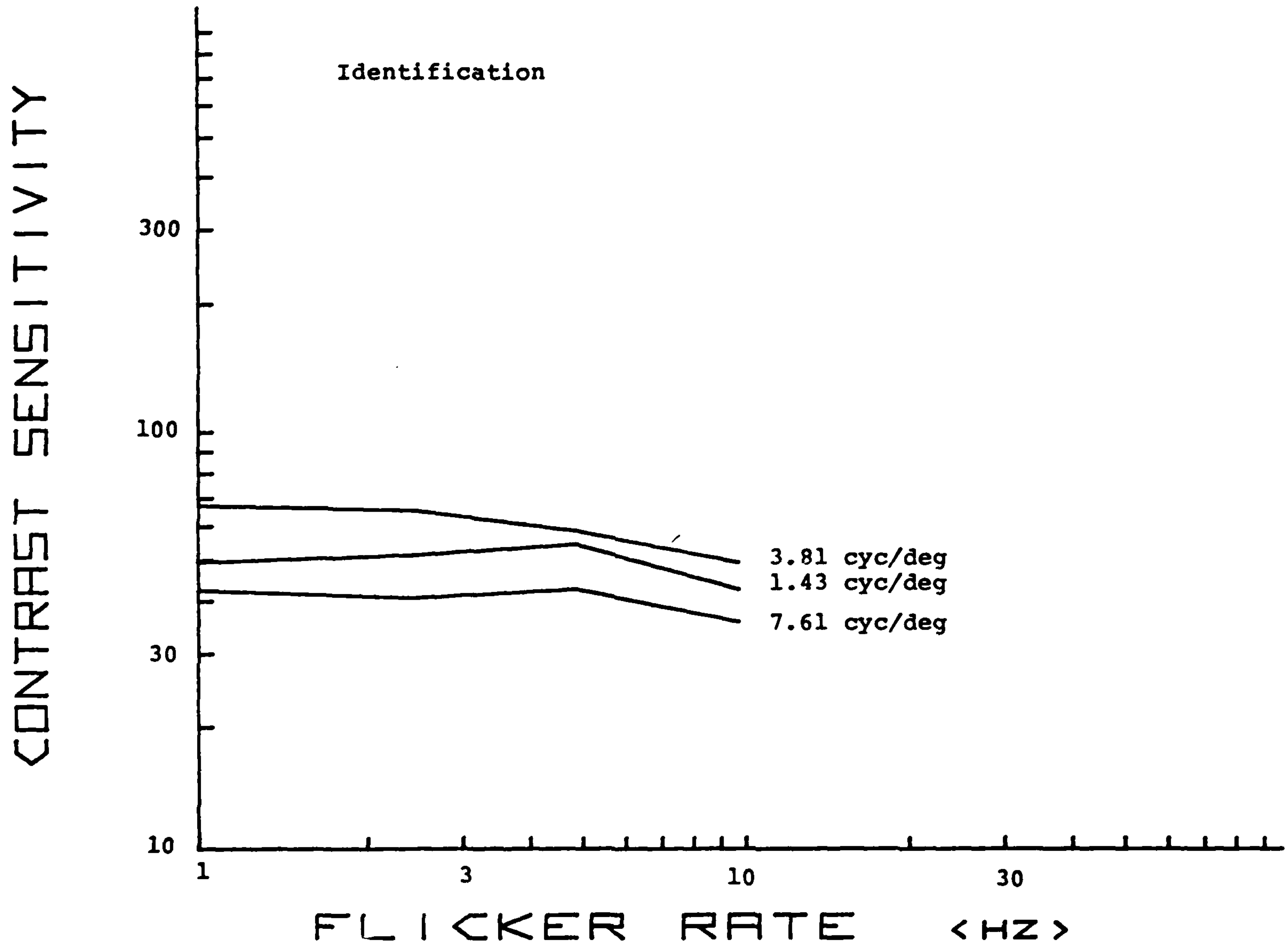
This finding accords well with the notion of a low spatial frequency/intermediate temporal frequency channel; i.e., the transient channel. At the intermediate (3.81 cycles/ degree) spatial frequency, the stimuli flickered at 1 Hz always yielded the highest sensitivities; however, the difference in sensitivity between them and the 5-Hz stimuli was quite small. At the highest (7.61 cycles/degree) spatial frequency there was virtually no difference in sensitivity between the 1-Hz and 5-Hz flickered stimuli. Stimuli flickered at 10 Hz always yielded the lowest sensitivities. In general, the contrast sensitivity functions obtained with moving sine-wave gratings were also the lowest at the 10-Hz drift rate. Thus, given the high sensitivity at intermediate spatial and temporal frequencies along with the crossover of the 5-Hz and 1-Hz functions at the lowest spatial frequencies and the general depression of the 10-Hz function, these data are in good agreement with CSFs obtained earlier with the moving sine-wave gratings and suggest that motion and flicker may be processed in common, or at least overlapping (cf. Pantle, 1978), channels of the human visual system. Green (1981) has also shown overlap in the human visual responses to flicker and motion.

Our data are replotted in Figures 43 and 44 with flicker rate shown on the abcissae and spatial frequency as the parameter. Figure 43 shows detection sensitivities only; Figure 44 identification sensitivities. As can be seen in the figures, the 3.81 cycles/degree stimuli yielded the highest sensitivities for both criteria at all flicker rates,

FIGURES 43-44: Contrast sensitivities in response to Snellen-letter stimuli of various fundamental spatial frequencies (separate functions in each figure) as functions of flicker rate. All stimuli were rotated to 0°. Data points are collapsed over four observers and over Snellen-letter stimuli. Figure 43: Detection sensitivities; Figure 44: Identification sensitivities.



Detection
3.81 cyc/deg
1.43 cyc/deg
7.61 cyc/deg
FLICKER RATE <HZ>
1
3
10
30
CONTRAST SENSITIVITY
10
30
100
300


Identification
CONTRAST SENSITIVITY
300
100
30
10
1
3
10
30
FLICKER RATE <HZ>
3.81 cyc/deg
1.43 cyc/deg
7.61 cyc/deg

followed by the 1.43 cycles/degree stimuli and the 7.6. cycles/degree stimuli respectively. The peak in both of the 1.43-cycles/degree functions at 5 Hz emphasizes the preference of the visual system for stimuli of low to intermediate spatial frequencies combined with intermediate temporal frequencies.

Except for the 1.43-cycles/degree identification-sensitivity curve, these functions decline over flicker rate with roughly equal slope. For detection, the decline is greatest for the 3.81-cycles/degree stimuli, dropping from a sensitivity of 97.67 at 1 Hz to 76.87 at 10 Hz; it is least for the 7.61-cycles/degree stimuli, going from 61.49 to 51.28. The detection sensitivity for the 1.43-cycles/degree stimuli declines from its peak of 70.71 at 5 Hz to 57.71 at 10 Hz. This pattern of results was repeated for the identification sensitivities. The average difference between detection and identification sensitivities in this experiment was 21.27.

Using the same logic applied by Ginsburg (1978) to determine the range of <u>spatial</u> frequencies above the detection spatial frequency that were used for identification, we determined the range of <u>temporal</u> frequencies (flicker rates) above the detection temporal frequency that are used for identification (excluding, of course, thresholds obtained with non-flickering stimuli). First we plotted contrast sensitivities for both detection and identification against linear temporal frequency. Next we determined the

the regression equation for each of the functions and the temporal-frequency intercept. The ratio of the detection-intercept to the identification-intercept gives the range of temporal frequencies above the detection-intercept that is used for identification. This procedure was followed for each of the three Snellen-letter fundamental spatial frequencies used in the present study.

As spatial frequency increases, the identification-to-detection threshold ratio decreased monotonically. For the 1.43 cycles/degree stimuli, the ratio was 1.72. Applying Ginsburg's type of analysis, this figure can be interpreted in the following way: Some range of temporal frequencies found by multiplying the temporal frequency at detection threshold by 1.72 is being used for identification. For example, if detection is achieved at a temporal frequency (flicker rate) of 3 Hz, identification should be best achieved at a flicker rate of 5.16 Hz. For the 3.81-cycles/degree stimuli, the ratio was 1.60; for the 7.61-cycles/degree stimuli, 1.07. Thus, the range of temporal frequencies used for identification relative to detection diminishes as a function of spatial frequency. A least squares regression analysis was performed (r=.89) to determine the spatial frequency at which the ratio of detection-intercept to identification-intercept on the temporal frequency axis would equal 1.0. This value was found to be 8.56 cycles/degree and it suggests that at and beyond a spatial frequency of 8.56 cycles/degree, detection and identification are achieved at the same

temporal frequencies.

That identification should be achieved at temporal frequencies <u>higher</u> than those used for detection at spatial frequencies below 8.56 cycles/degree is a finding that is both intriguing and difficult to interpret, given the evidence suggesting that transient channels (motion and flicker detection) prefer low spatial frequencies and moderate temporal stimulation while sustained channels (pattern detection) prefer higher spatial frequencies and <u>little</u> temporal stimulation. We offer the following interpretation of these findings which has yet to receive adequate empirical support: We assume that for spatial frequencies below 8.56 cycles/degree, detection of the Snellen-letter stimuli is achieved by transient mechanisms sensitive to flicker. However, since the sustained mechanisms that identify the stimulus at some higher spatial frequency do not respond well to flicker they can be stimulated only by a) raising the contrast of the stimulus or by b) increasing the flicker rate of the stimulus so that several "presentations" of the stimulus occur within the integration period of the sustained mechanisms (cf. Petersik & Pantle, 1979). If this interpretation is true, it explains why the detection-intercept to identification-intercept ratio on the temporal frequency axis is greater than 1.0. As spatial frequency increases and the mechanisms involved in detection become more sustained-like (Legge, 1978), less of an increase in temporal frequency would be required before enough "presentations" occur within the integration period of sustained

mechanisms to achieve identification. Hence, the ratio comes closer and closer to 1.0. At a spatial frequency of 8.56 cycles/degree, sustained mechanisms essentially detect and identify stimuli flickering several times within single integration period; the ratio reaches 1.0 at this value of spatial frequency.

B. Spatial-frequency adapt/Snellen-letter test

If it is true that the spatial-frequency content of a complex visual stimulus determines the nature of the visual system's response to that stimulus (i.e., if the visual system performs something like a local Fourier analysis), then it ought to be possible to bias the visual system's response to that stimulus by prior adaptation to certain spatial frequencies. Hence, in the following experiment, two observers (MB and RF) were adapted to each of a number of sine-wave gratings of different frequencies and made subsequent contrast-threshold adjustments in response to Snellen letters of different sizes.

1. Methods of procedure

The same apparatus described in earlier sections of this report was used in the present experiment. One channel of the system contained either the adapting grating or the test Snellen-letter (at alternate times), while the remaining channel was the blank (or luminance) channel.

At the beginning of any experimental session, the observer adapted to a randomly selected <u>horizontally</u> oriented sine-wave grating for a period of 7 min. The contrast of the adapting grating was always approximately .85. Following the adaptation period, the subject closed his

eyes while the experimenter entered a randomly selected Snellen-letter (either E or L of different sizes) into the stimulus channel and lowered its contrast to 0.00. Next the observer made an identification-threshold setting after which the experimenter replaced the letter with the grating and raised its contrast to .85. The subject then re-adapted to the grating for a period of 3 min. Thereafter, adaptation was interrupted every 3 min. for an identification-threshold setting with a new Snellen-letter stimulus. Any individual test (i.e., identification threshold) sequence required about 30 sec of time. Any individual experimental session lasted no longer than 60 min. Luminance of the background of the display was held constant at 20 cd/m$^2$. Viewing distance was again 196.2 cm. Viewing was monocular with the preferred eye.

Separate sessions were run for adapting frequencies of 0.72, 1.04, 1.56, and 2.08 cycles/degree. Test stimuli consisted of Es and Ls having fundamental spatial frequencies of 1.43, 2.28, 3.81, and 7.61 cycles/degree. In addition, two stimuli having fundamental spatial frequencies of 1.43 and 3.81 cycles/degree were tested after adaptation to gratings of 0.52, 2.6, and 5.2 cycles/degree. The order of adaptation and testing was randomly determined for each subject. Five threshold settings were obtained from each subject at each combination of adapting and test spatial frequency.

We obtained identification thresholds only, because our adapting stimuli were one-dimensional whereas the test

letters were two-dimensional and detection could occur in response to information in the unadapted orientation (i.e., in response to the vertical bars in the letters). However, discrimination, and therefore identification, of the letters E and L relies mainly upon information in the horizontal direction (i.e., upon horizontal bars). Thus it was our hope to bias the response of horizontally selective spatial-frequency channels (Blakemore & Campbell, 1969) by adaptation to horizontal sine-wave gratings. If such adaptation has an effect, it would be revealed in identification tasks, but not in detection tasks.

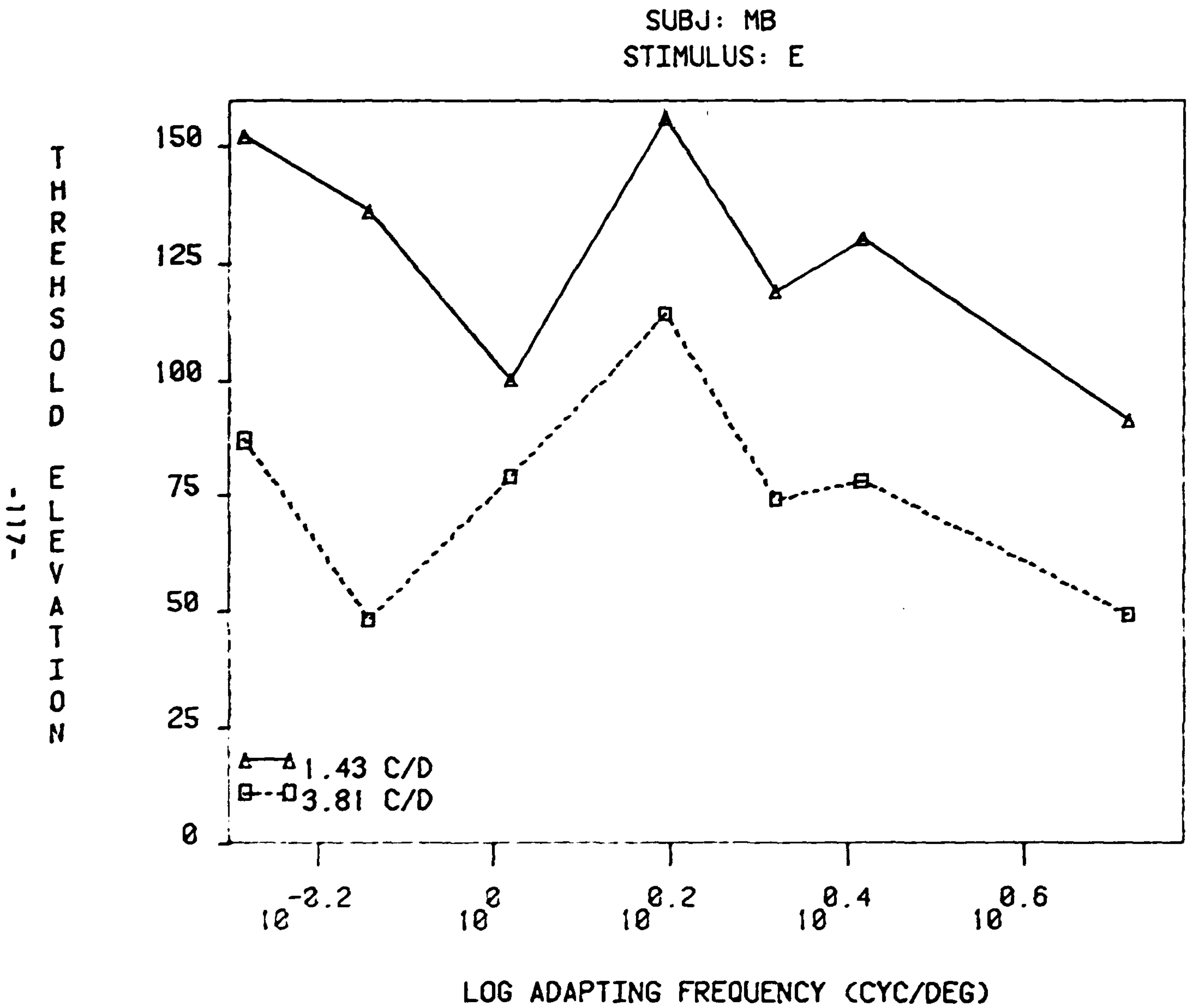
2. Results and discussion

Threshold elevations were calculated for each observer at each test-letter fundamental spatial frequency and adapting spatial frequency according to the formula: threshold elevation = 100 ("adapted threshold" - "unadapted threshold")/ "unadapted threshold." (e.g., Petersik, Regan, & Beverley, 1981.)

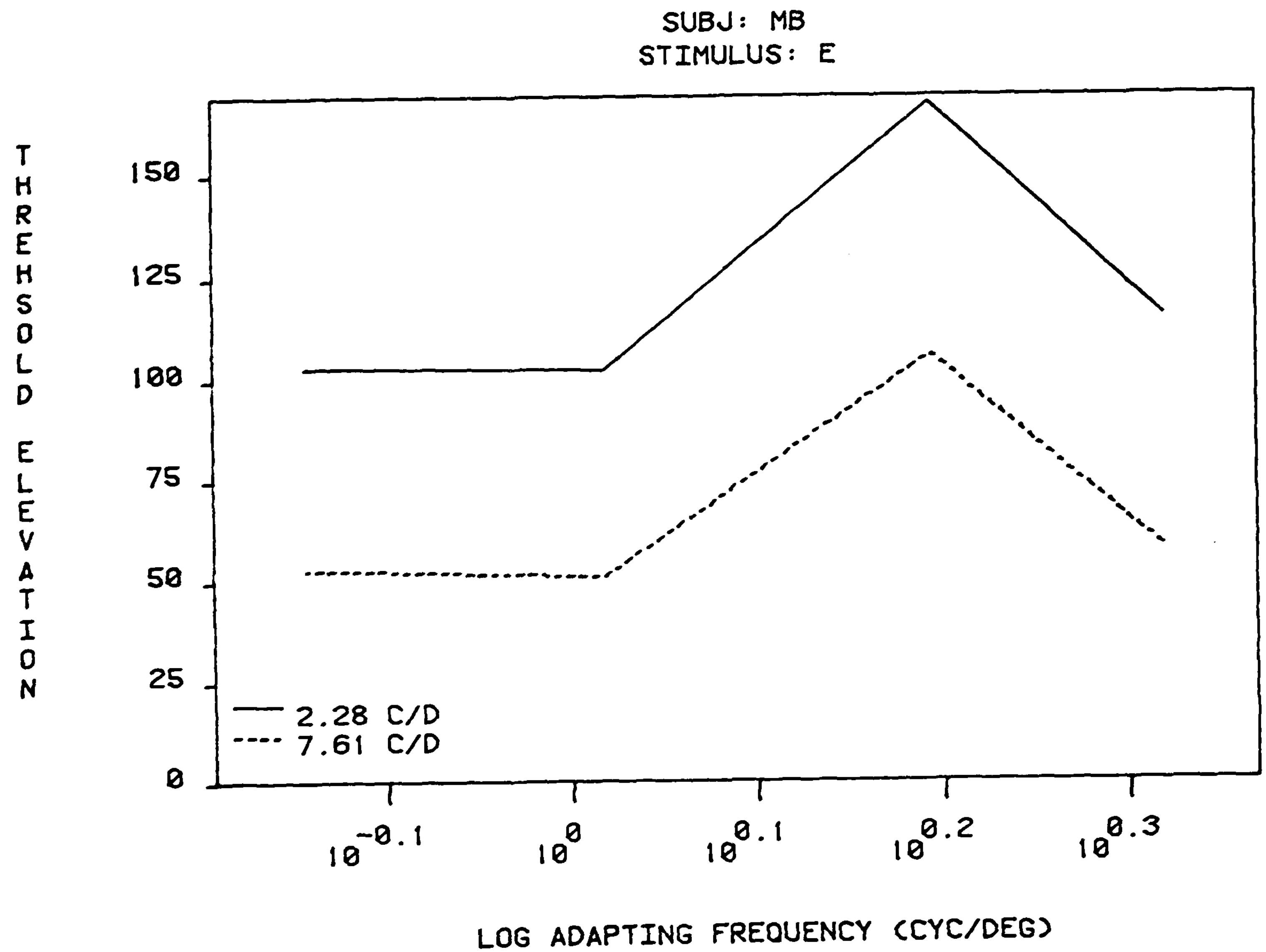
Results are shown here for subject MB only. RF's results, while similar in pattern, were much reduced in magnitude relative to MB's threshold elevations.

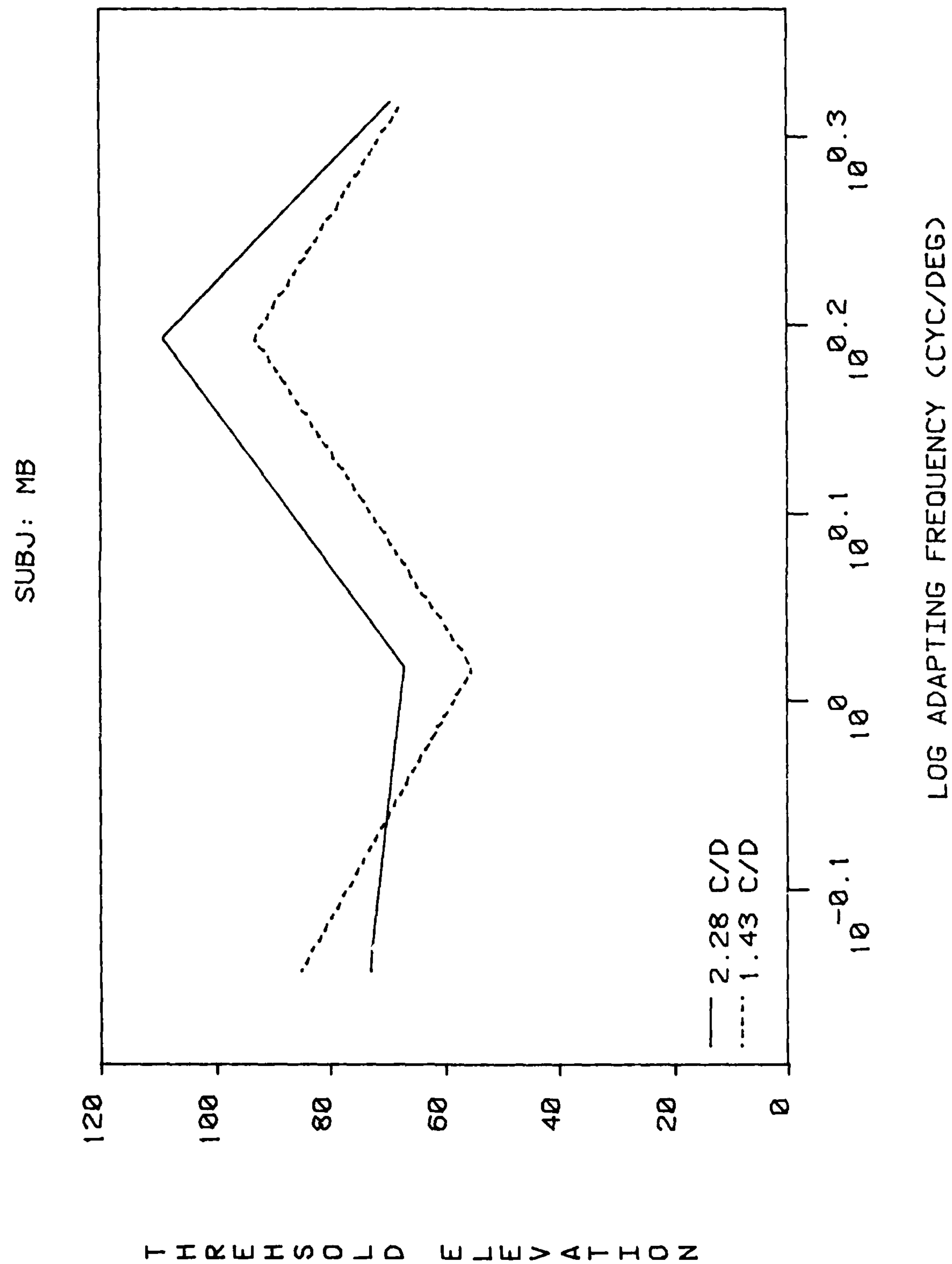
We believe that there was little or no frequency-specific adaptation in the present experiment for the following reasons: 1) RF showed little threshold elevation after adaptation to any grating; 2) MB showed maximum threshold elevation in response to the 1.56 cycles/degree adaptation grating, irrespective of the fundamental spatial frequency of the test letter (see Figures 45 through 48);

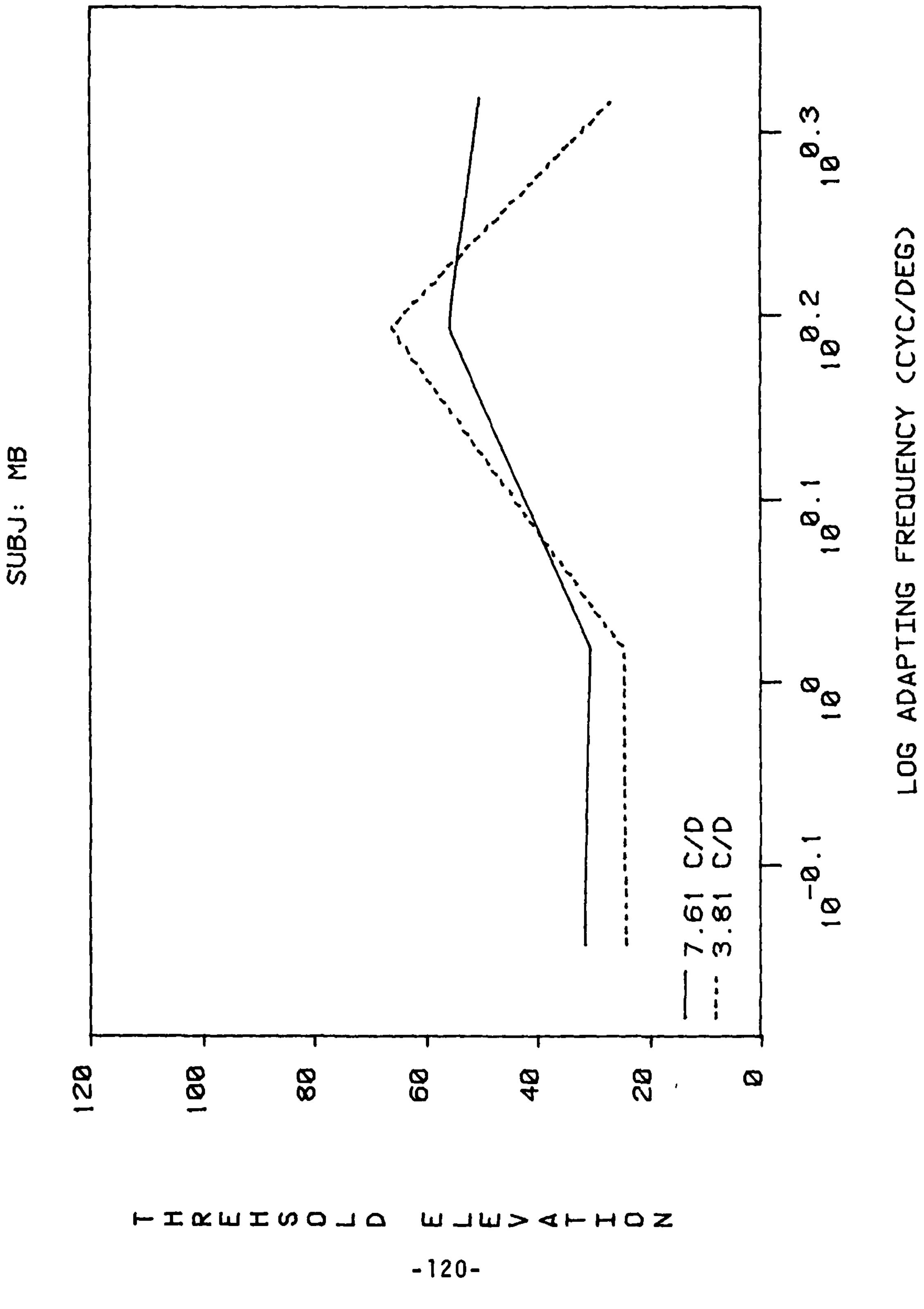
FIGURES 45-48: Threshold elevation of Snellen-letter stimuli of various fundamental spatial frequencies (separate functions) as functions of log adapting spatial frequency. Observer MB. Figures 45 & 46: Snellen-letter 'E'. Figures 47 & 48: Snellen-letter 'L'.



SUBJ: MB
STIMULUS: E
THREHSOLD ELEVATION
150
125
100
75
50
25
0
1.43 C/D
3.81 C/D
10^-0.2
10^0
10^0.2
10^0.4
10^0.6
LOG ADAPTING FREQUENCY (CYC/DEG)


SUBJ: MB
STIMULUS: E
THREHSOLD ELEVATION
150
125
100
75
50
25
0
2.28 C/D
7.61 C/D
$10^{-0.1}$
$10^{0}$
$10^{0.1}$
$10^{0.2}$
$10^{0.3}$
LOG ADAPTING FREQUENCY (CYC/DEG)


SUBJ: MB
2.28 C/D
1.43 C/D
THRESHOLD ELEVATION
120
100
80
60
40
20
0
$10^{-0.1}$
$10^{0}$
$10^{0.1}$
$10^{0.2}$
$10^{0.3}$
LOG ADAPTING FREQUENCY (CYC/DEG)


SUBJ: MB
THRESHOLD ELEVATION
LOG ADAPTING FREQUENCY (CYC/DEG)
— 7.61 C/D
--- 3.81 C/D
0
20
40
60
80
100
120
$10^{-0.1}$
$10^{0}$
$10^{0.1}$
$10^{0.2}$
$10^{0.3}$

3) MB showed a maximum elevation of the thresholds for letters having a fundamental spatial frequency of 2.28 cycles/degree at all adaptation spatial frequencies (see Figure 49). The latter findings are examined in more detail below.

Figures 45 through 48 show the results of this experiment for observer MB. In each figure, threshold elevation is plotted as a function of log spatial frequency. Each curve in the figures shows the results obtained with a test letter (E or L) of a given fundamental spatial frequency. Figure 45 shows the most complete set of results for the letter E (1.43 and 3.81 cycles/degree). As can be seen, maximum elevation occurred in response to adaptation to sine-wave gratings of 1.56 cycles/degree ($10^{.19}$), followed by peaks at both .52 ($10^{-.28}$) and 2.6 ($10^{.41}$) cycles/degree. These peaks occur at roughly an octave above and below the fundamental frequency of 1.43 cycles/degree. The peaks at .52, 1.56, and 2.6 cycles/degree are .14, .41, and .68 times the fundamental frequency of 3.81 cycles/degree respectively.

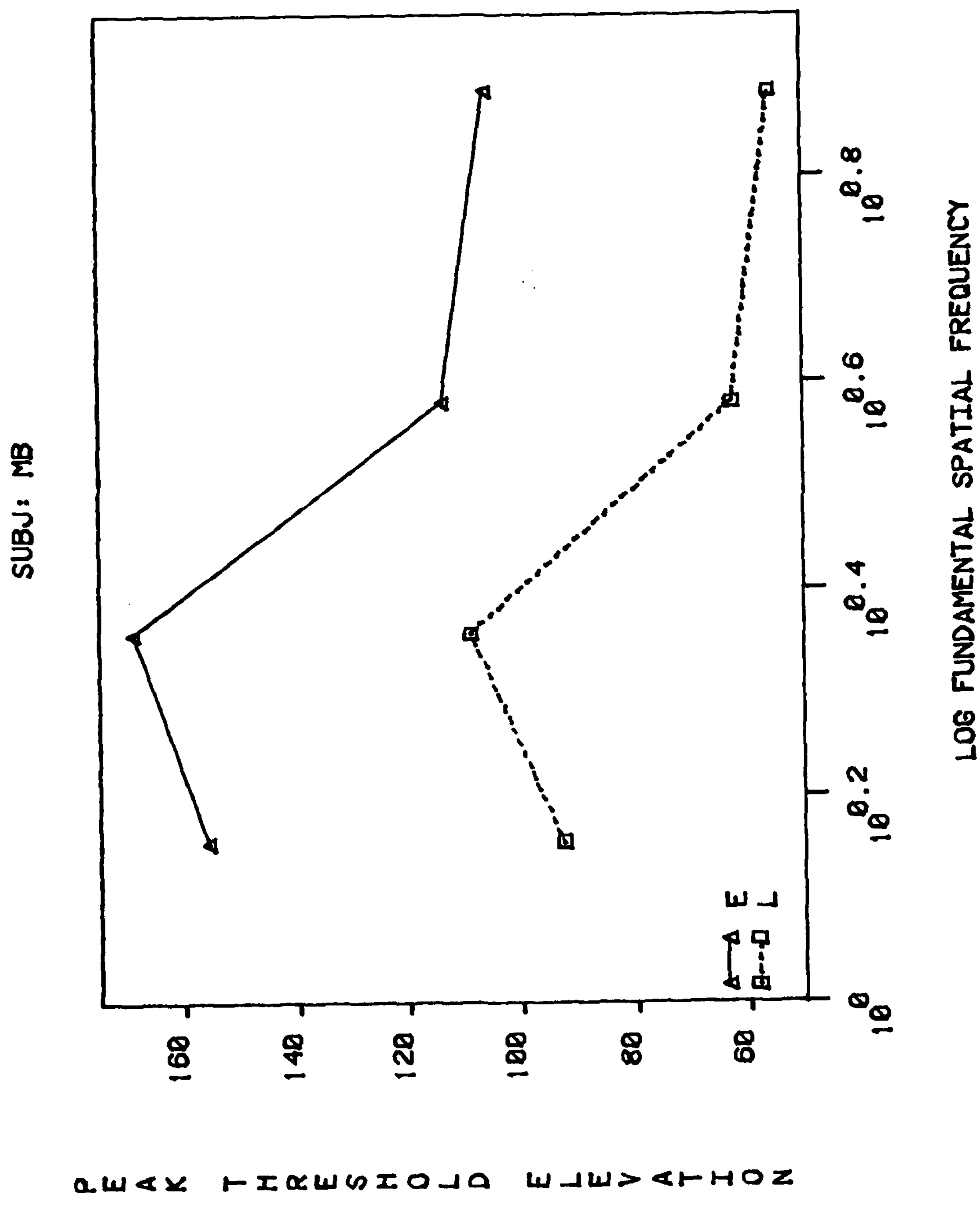
Figure 46 shows comparable results for the letter E having fundamental spatial frequencies of 2.28 and 7.61 cycles/degree. Again, peak elevation occurred at 1.56 cycles/degree. However, relatively less threshold elevation was apparent at high and lower adapting frequencies. Similar findings are shown in Figures 47 and 48 for the letter L.

In an effort to understand these findings, we plotted

the peak threshold elevation of the letters E and L as a function of the log fundamental spatial frequency of those letters. These results are shown in Figure 49. The first finding apparent in this figure is that the Es were always subject to more threshold elevation than were the Ls. This is probably because of the periodic nature of the horizontal bars in the Es. Secondly, the 2.28 ($10^{.36}$) cycles/degree stimuli always showed the most elevation, followed by the 1.43 ($10^{.16}$), 3.81 ($10^{.58}$) and 7.61 ($10^{.88}$) cycles/degree stimuli. In MB's static CSF, frequencies between 1.43 and 2.28 cycles/degree are in the range of the low-frequency falloff. Those between 3.81 and 7.61 cycles/degree are near the peak of the CSF. Thus, the relatively less sensitive channels responding to lower spatial frequencies may have suffered more after adaption than those near the peak of the CSF.

These results suggest that MB may have undergone more of a pattern-specific than a frequency-specific type of adaptation. This conclusion is based upon the following logic: Although the frequencies of the adapting gratings in this experiment were never identical to the fundamental frequencies of the test letters, threshold elevation of the letter E could have occurred if 1) the bars of the adapting grating completely overlapped the spacing of the bars in the test letter E, or if 2) the spacing of the bars in the adapting grating partially overlapped one or more spacings (bars) of the test letter E, thereby potentially obscuring its visibility upon presentation. By

FIGURE 49: Peak threshold elevation of stimulus letters 'E' and 'L' (separate functions) as functions of log fundamental spatial frequency. Observer MB.


SUBJ: MB
PEAK THRESHOLD ELEVATION
160
140
120
100
80
60
E
L
$10^{0}$
$10^{0.2}$
$10^{0.4}$
$10^{0.6}$
$10^{0.8}$
LOG FUNDAMENTAL SPATIAL FREQUENCY

way of analogy, consider two overlapping transparencies, one of which contains the letter E and one of which contains a horizontal grating (neural afterimage?). Identification would certainly be impeded if, at any point in time as the transparencies are shifted over one another, one or more bars of the letter are obscured by the grating. Such a situation obtains for gratings of many different spatial frequencies.

Although this account could explain the threshold elevation we found with the letter E, it seems difficult to use it to explain the lesser elevation obtained with the letter L. We believe that the periodic nature of the letter E accounts for the greater threshold elevation obtained with it. That is, the E offers more opportunity to be obscured. On the other hand, the L has a significant gap above the lower horizontal bar, and this gap would become more apparent as the grating (transparency) is shifted over the stimulus letter. Georgeson (1976) has described the sort of "neural afterimages" alluded to here, although he calls them "psychophysical hallucinations." In short, he found that adaptation to vertical sinusoidal gratings results in the following subsequent aftereffects: horizontal streaming; the appearance of a roughly sinusoidal grating about 1.5 octaves above the adapting frequency; the appearance of two sets of diagonal lines. Any or all of these effects could have contributed to our obtained results.

What has been described is analogous to a two-dimensional cross-correlation of each letter with a horizontal grating. In practice, the cross-correlation function would be greater for an E with a grating than for an L with the same grating, reflecting the periodicity of each. However, that high degree of periodicity renders the E and the grating less distinguishable than some less periodic stimulus and the grating.

In short, we propose that adaptation in the present experiment consisted of neural fatigue of pattern-analyzing mechanisms (e.g., horizontal edge detectors). Such adaptation is thought to establish something like a neural after-image, which renders the detection and identification of subsequently presented contours in the same orientation more difficult. The notion that edge-detectors and pattern-analyzing mechanisms are compatible with spatial-frequency analysis as ways of describing the operation of the visual has been argued by Petersik and Grassmuck (in press).

## VI. SUMMARY OF FINDINGS AND CONCLUSIONS

This section summarizes some of the main findings and conclusions of this report and should not be considered to be exhaustive. Furthermore, this section is concerned primarily with results related to the detection and identification of Snellen-letter targets.

### A. Stationary Stimuli

1) Detection and identification CSFs for Snellen-letter targets were generally inverted U-shaped functions of fundamental spatial frequency, irrespective of rotation. However, the peaks of these functions shifted from approximately 2.5 cycles/degree to 5.2 cycles/degree (in the horizontal dimension) with rotations from 0° to 75°. It was hypothesized that the shift in peak frequency could be explained by the fact that information in the vertical dimension does not change with rotation about the Y-axis and can be used in detection and identification tasks. Thus, letters from a given set-size (e.g., large, medium, small, etc.) may have remained optimal stimuli despite rotation.

2) For stimuli rotated to 0° and 15°, there were almost constant differences (on log-log axes) between the sensitivities for detection and identification at all spatial frequencies. This suggested that our observers may have used for identification spatial frequencies less than 1.5 times those used for detection. Ginsburg (1978) determined that the range of frequencies used for identification was 1.5-2.5 times higher than the frequencies used for detection.

3) Beyond 30° (and particularly at 75°) rotation, the decline in sensitivity beyond the peak spatial frequency is more rapid for identification than for detection. This suggested that either a) with greater rotation the information available for detection becomes attenuated, or b) with greater rotation the information required for identification becomes shifted to higher spatial frequencies.

4) The slope relating the detection-to-identification threshold contrast ratio to log spatial frequency changes from -.088 at 0° rotation to -.43 at 75° rotation. This suggested that the ratio of spatial frequencies used for the identification vs. detection of letters changed from something less than 1.5 at 0° to 1.5-2.5 at 75°.

5) By plotting the regression lines of the detection and identification sensitivities as functions of <u>linear</u> spatial frequency and then determining the ratio of their spatial frequency intercepts, we were able to estimate the bandwidth of the identification-to-detection threshold ratio. As predicted above, bandwidths were less than 1.5 (1.1) for 0°-rotation stimuli and were greater than 1.5 for 75°-rotation stimuli.

6) Observer MS showed intermediate-to-high spatial frequency losses of sensitivity when tested with sine-wave gratings. These losses were reflected in depressed peaks and larger separations between detection and identification in MS's CSFs with Snellen letters.

7) Together, variations in the size and rotation of Snellen-letter stimuli accounted for a decline in detection

sensitivity of roughly two-thirds; in identification sensitivity, of almost three-fourths.

B. Moving Stimuli

1) For frequencies at and below 20 Hz, temporal frequency (or velocity) had little effect on detection and identification contrast sensitivity for Snellen-letter stimuli with a fundamental spatial frequency of 2.28 cycles/degree. Beyond 20 Hz, both detection and identification sensitivities declined with increasing temporal frequency, although the rate of decline was greater for identification sensitivity than for detection sensitivity. The above finding was explained by assuming that members of a population of velocity-sensitive elements within the visual system were equally stimulated by letters shifting at rates less than 20 Hz.

2) With different temporal frequencies, the ratio of detection contrast to identification contrast was roughly constant (≈ .73) up to a cutoff of 20 Hz. Beyond 20 Hz, the ratio declined gradually to a low of .39.

3) For Snellen-letter stimuli of 2.28 cycles/degree, MS's CSFs were essentially normal over variations in temporal frequency. This would be expected if MS had normal transient mechanisms in his visual system.

4) Both spatial frequency and velocity of moving Snellen-letter stimuli were varied in one experiment. At a velocity of 1.67 degrees/second, identification sensitivity did not decline over the range of spatial frequencies (1.43-3.81 cycles/degree). At 16.61 degrees/second, a substantial

decline in identification sensitivity was apparent at 3.81 cycles/degree. Over this range of spatial frequencies, detection sensitivity was not influenced by velocity. These findings are consistent with the concept of sustained and transient channels in human vision.

5) With motion, CSFs to Snellen letters lost the low spatial-frequency falloffs apparent in the curves for 0°-rotation stationary letters.

6) Detection-to-identification threshold contrast bandwidths rose from 1.1 for 0°-rotation stationary stimuli to 2.88 for 0°-rotation stimuli drifting at 16.61 degrees/second. This increase was accompanied by an increase in both detection and identification sensitivity at low fundamental spatial frequencies with 16.61-degrees/second movement and by a depression of identification sensitivity that is accelerated at high spatial frequencies by movement.

7) At higher velocites, MS's identification sensitivity was unusually depressed over the range of spatial frequencies. This was expected due to MS's apparently abnormal sustained system.

8) Slow movement (1.67 degrees/second) enhanced detection sensitivity relative to stationary conditions, and to a lesser extent, identification sensitivity relative to stationary conditions. Fast movement (16.61 degrees/second) enhanced detection sensitivity at lower spatial frequencies and depressed it somewhat at the highest frequency. It also depressed identification sensitivity relative to stationary conditions.

9) Still faster motion (33.2 degrees/second) further depressed identification sensitivity relative to stationary conditions, and to a lesser extent it also depressed detection sensitivity.

C. Flickering Stimuli

1) At the lowest fundamental spatial frequency of Snellen-letter stimuli (1.43 cycles/degree), stimuli flickered at 5 Hz always yielded the highest sensitivities. At the intermediate spatial frequency (3.81 cycles/degree), stimuli flickered at 1 Hz always yeilded the highest sensitivities. At the highest spatial frequency, both the 1-Hz and 5-Hz flicker rates yielded the highest sensitivities. Stimuli flickered at 10 Hz always yielded the lowest sensitivities. These results agreed well with the data obtained with moving sine-wave gratings.

2) Using the logic presented by Ginsburg (1978) for spatial frequencies, we determined that the optimum temporal frequency used for the identification of flickering Snellen-letter stimuli having a fundamental spatial frequency of 1.43 cycles/degree was 1.72 times the optimum temporal frequency used for detection. The corresponding figure for stimuli with a fundamental spatial frequency of 3.81 cycles/degree was 1.60; for 7.61 cycles/degree, 1.07. At and beyond 8.56 cycles/degree, detection and identification should be optimal at the same temporal frequency. It was hypothesized that optimum temporal frequencies for identification are sometimes below those for detection because sustained mechanisms are stimulated more frequently during a single integration period.

D. Spatial-Frequency Adaptation

1) Of two observers, one showed significant identification-threshold elevation of Snellen-letter stimuli after adaptation to gratings of various spatial frequencies; the other showed a similar pattern of results, but with much reduced magnitude.

2) Observer MB showed a maximum threshold elevation of letters having a fundamental spatial frequency of 2.28 cycles/degree at all adaptation spatial frequencies.

3) Observer MB showed maximum threshold elevation after adapting to a 1.56-cycles/degree grating, irrespective of the fundamental spatial frequency of the test letter.

4) The above data were taken as evidence for pattern-specific, retinal-locus independent adaptation rather than frequency-selective adaptation.

## VII. IMPLICATIONS

One outstanding finding of these experiments that has not been given due attention previously is the fact that, over large ranges of rotations and velocities, the effects of rotation and motion on detection and identification contrast sensitivity were minimal. In particular, under everyday conditions of observation (i.e., with high contrasts), the visual performance of a normal observer should not deteriorate significantly until a rotation of 60°-75° is reached or until a velocity beyond about 10 degrees/second is reached. The joint effects of rotation and motion appear to be some nonlinear function of the independent effects, since their joint effects are not significant also until relatively extreme values are reached.

These findings are consistent with the conjecture that the visual system is designed to recognize objects in three-dimensional space (Johansson, 1977). They are also consistent with Gibson's (1957) belief that the visual environment affords the observer sufficient information (e.g., perspective) to nearly instantaneously determine the slant and identity of objects within the visual field. Indeed, previous experiments in this laboratory (Petersik, 1979) have determined that three-dimensional object constancy can be maintained in the presence of high levels of visual noise. At the time, it was argued that <u>dynamic perspective</u>, or the information provided by movement and perspective together, is a significant factor in the

maintenance of three-dimensional object constancy. In short, we are finding that the foreshortening and perspective transformations consequent to rotation and movement are rich in information regarding object identity.

How such findings can be incorporated into a general theory of pattern recognition is problematic. Clearly, Ginsburg's (1978) most recent development, based upon two-dimensional frequency filtering of static images, is insufficient since it ignores changes in the spatial tuning function of the visual system that occur in response to moving stimuli. Furthermore, although it is relatively easy to determine the spatial-frequency content of stimuli that have been rotated, Ginsburg's model cannot yet account for the information contained in such perspective transformations.

This report provides data which must be accounted for by a model of visual recognition -- data obtained with both rotated and moving stimuli. Much of the data can be accounted for by what is already known about the spatio-temporal properties of sustained and transient visual mechanisms. Yet these mechanisms do not constitute, in and of themselves, a <u>model</u> of visual recognition. One step of the model-building process would be to prepare filtered versions of Snellen-letter stimuli rotated to various angles and then to determine the number of cycles/object required for both detection and identification (as Ginsburg has already done for non-rotated stimuli). Another step in the

process would be to measure the detection and identification spatio-temporal response functions for Snellen-letter stimuli simulated to be rotating in depth. Such stimuli are much richer in dynamic perspective information than those employed in the present study. Finally, the filtering theory of Ginsburg must be extended to include both pattern- and movement-analyzing mechanisms.

Regarding the assessment of pilot trainees, it is important that such individuals be tested with moving, as well as stationary, patterns since visual deficits in the human transient system, independent of the status of the sustained system, are known to occur.

## References


Blakemore, C., & Campbell, F. W. On the existence of neurones in the human visual system selectively sensitive to the orientation and size of retinal images. Journal of Physiology, 1969, 203, 237-260.

Braddick, O., Campbell, F. W., & Atkinson, J. Channels in vision: Basic aspects. In R. Held, H. W. Leibowitz, and H.L. Teuber (Eds.), Handbook of sensory physiology, Vol. VIII: Perception. New York: Springer-Verlag, 1978.

Breitmeyer, B. G., & Ganz, L. Implications of sustained and transient channels on visual pattern masking, saccadic suppression, and information processing. Psychological Review, 1976, 83, 1-31.

Campbell, F. W., & Robson, J. G. Application of Fourier analysis to the visibility of gratings. Journal of Physiology, 1968, 197, 551-566.

Estevez, O., & Cavonius, C. R. Low-frequency attenuation in the detection of gratings: Sorting out the artifacts. Vision Research, 1976, 16, 497-500.

Fritsch, K., & Keck, M. Grating generation by microcomputer. Vision Research, 1978, 18, 1083-1085.

Ganz, L., & Lange, A. Changes in motion sensitivity of cat visual cortex neurons during the course of dark adaptation. Presented at the Spring Meeting of the Association for Research in Vision and Ophthalmology, Sarasota, Florida, 1973.

Georgeson, M. A. Psychophysical hallucinations of orientation and spatial frequency. Perception, 1976, 5, 99-111.

Gibson, J. J. Optical motions and transformations as stimuli for visual perception. _Psychological Review_, 1957, _64_, 288-295.

Ginsburg, A. P. _Visual information processing based on spatial filters constrained by biological data_. AMRL-TR-78-129. Wright-Patterson Air Force Base, Ohio: Aerospace Medical Research Laboratory, December, 1978.

Ginsburg, A. P., Cannon, M., & Nelson, M. Suprathreshold processing of complex visual stimuli: Evidence for linearity in contrast perception. _Science_, 1980, _208_, 619-621.

Graham, N. Psychophysics of spatial-frequency channels. In M. Kubovy & J. R. Pomerantz (Eds.), _Perceptual organization_. Hillsdale, New Jersey: Lawrence Erlbaum Associates, 1981.

Green, M. Psychophysical relationships among mechanisms sensitive to pattern, motion, and flicker. _Vision Research_, 1981, _21_, 971-984.

Grusser, O. J., & Grusser-Cornehls, U. Neuronal mechanisms of movement perception and some psychophysical and behavioral correlations. In R. Jung (Ed.), _Handbook of sensory physiology_, _Vol. VII/3A_. Berlin: Springer-Verlag, 1973.

Guzman, O., & Steinbach, J. J. Manipulating the contrast of sine wave gratings and other light distributions using polaroid. _Vision Research_, 1981, _21_, 1025-1028.

Hubel, D. H., & Wiesel, T. N. Receptive fields and functional architecture in two nonstriate visual areas (18 and 19) of the cat. _Journal of Neurophysiology_, 1965, _28_, 229-289.

Johansson, G. Spatial constancy and motion in visual perception. In W. Epstein (Ed.), Stability and constancy in visual perception. New York: John Wiley & Sons, 1977.

Kelly, D. H. Flicker. In D. Jameson & L. M. Hurvich (Eds.), Handbook of sensory physiology, Vol. VII/4: Visual psychophysics. Berlin: Springer-Verlag, 1972.

Kulikowski, J. J., & Tolhurst, D. J. Psychophysical evidence for sustained and transient detectors in human vision. Journal of Physiology, 1973, 232, 149-162.

Legge, G. Sustained and transient mechanisms in human vision: temporal and spatial properties. Vision Research, 1978, 18, 69-82.

Movshon, J. A. Velocity preferences of simple and complex cells in the cat's striate cortex. Journal of Physciology, 1974, 242, 121-123P.

Nilsson, T., Nelson, T. M., & Richmond, C. F. Evidence of visual channels selectively sensitive to temporal frequenct. Paper presented at the annual convention of the Psychonomic Society, 1974.

Pantle, A. J. Flicker adaptation. I. Effect on vissual sensitivity to temporal fluctuations of light intensity. Vision Research, 1971, 11, 943-952.

Pantle, A. J. Research on visual perception of complex and dynamic imagery. AMRL-TR-77-83. Wright-Patterson Air Force Base, Ohio: Aerospace Medical Research Laboratory, November, 1977.

Pantle, A. J. Temporal frequency response characteristics of motion channels measured with three different psychophysical techniques. Perception & Psychophysics, 1978, 24, 285-294.

Pantle, A. J. Analysis of dynamic visual processing. Report F33615-77-C-0528. Wright-Patterson Air Force Base, Ohio: Aerospace Medical Research Laboratory, April, 1980.

Pantle, A. J., & Sekuler, R. Size-detecting mechanisms in human vision. Science, 1968, 162, 1146-1148.

Petersik, J. T. The effects of image motion and rotation on contrast sensitivity in a letter detection and identification task. In USAF/SCEEE Summer Faculty Research Program. Research Reports, Volume II. Bolling Air Force Base, D.C.: Air Force Office of Scientific Research, 1980.

Petersik, J. T. Three-dimensional object constancy: Coherence of a simulated rotating sphere in noise. Perception & Psychophysics, 1979, 25, 328-335.

Petersik, J. T. Possible role of transient and sustained visual mechanisms in the determination of similarity judgments. Perceptual and Motor Skills, 1978, 47, 683-698.

Petersik, J. T. Mechanisms controlling sensations of depth and direction in moving perspective-transformation displays. Unpublished Ph.D. dissertation, Miami University, 1978.

Petersik, J. T., Beverley, K. I., & Regan, D. Contrast sensitivity of the changing-size channel. Vision Research, 1981, 21, 829-832.

Petersik, J. T., & Grassmuck, J. High fundamental spatial frequencies and edges have different perceptual consequences in the "group/end-to-end" movement phenomenon. Perception, in press.

Petersik, J. T., & Pantle, A. J. Factors controlling the competing sensations produced by a bistable stroboscopic motion display. Vision Research, 1979, 19, 143-154.

Pettigrew, J. D., Nikara, T., & Biship, P. O. Responses to moving slits by single units in cat striate cortex. Experimental Brain Research, 1968, 6, 373-390.

Sekuler, R. Spatial vision. Annual Review of Psychology, 1974, 25, 195-232.

Sekuler, R., Pantle, A., & Levinson, E. Physiological basis of motion perception. In R. Held, H. W. Leibowitz, and H.-L. Teuber (Eds.), Handbook of sensory physiology, Vol. VIII: Perception. New York: Springer-Verlag, 1978.

Schade, O. H. Optical and photoelectric analog of the eye. Journal of the Optical Society of America, 1956, 46, 721-739.

Tolhurst, D. J. Separate channels for the analysis of the shape and movement of a moving visual stimulus. Journal of Physiology, 1973, 231, 231-248.

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